2013-12

Applying and measuring the value of utility modeling in defense acquisition decision making

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http://hdl.handle.net/10945/38889

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

APPLYING AND MEASURING THE VALUE OF UTILITY MODELING IN DEFENSE ACQUISITION DECISION MAKING

by

Nathan P. Burgess
Keith A. Jordan

December 2013

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REPORT DOCUMENTATION PAGE		*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2013	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE APPLYING AND MEASURING THE VALUE OF UTILITY MODELING IN DEFENSE ACQUISITION DECISION MAKING	**5. FUNDING NUMBERS** R8FVK
6. AUTHOR(S) Nathan P. Burgess and Keith A. Jordan	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited	**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This research project is intended to determine if utility modeling could be used within the Department of Defense acquisition community. The primary effort of this research is to create a linear programming-based utility model that could assist a program manager in making purchase decisions. The final solution, given all available data regarding cost, schedule impacts, unique program constraints, and quality factors will be the optimal allocation of budgetary resources to achieve the best overall value for the end user and taxpayer. Data for this research were obtained from the Apache Block III Modernization Program after which a utility model was created to assess the utility of linear programming in the DoD acquisition decision-making process. The model compared 16 unique potential upgrades from the Apache Block III Modernization Program against each other and determined an optimal solution given the unique conditions of the program.

Utility modeling proved to be an effective tool to help program managers make better purchase decisions. Utility modeling, coupled with sensitivity analysis, weighted utility modeling, and decision support analysis, has the ability to optimize resource allocation decisions thus maximizing overall value and reducing waste. This research project identified opportunities for further exploration into project management forecasting, game theory and retroactive program analysis.

14. SUBJECT TERMS Acquisition, Apache Block III, Evolutionary Acquisition, Block Upgrades, Integer Programming, Linear Programming, Major Defense Acquisition Program, Multiple Criteria Decision Making, Program Manager, Program Management, Quality Index Score, Retroactive Program Analysis, Utility Model, Weighted Utility Modeling	**15. NUMBER OF PAGES** 93
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
Unclassified	Unclassified	Unclassified	UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF BUSINESS ADMINISTRATION

from the

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ACKNOWLEDGEMENTS

We would like to thank LTC Brian C. Stehle (product manager, Apache Block III, Modernization and Development) for his tremendous support for this project as well as that of his staff. Without his input, feedback, real-world data, and professionalism, this project would not have been possible.

We would also like to thank the Acquisition Research Program (ARP) for its support in making the project possible. Without the funding and other resources provided to us, this project would not have been as successful.

We would like to thank our advisors for their guidance and expertise throughout this process.

Finally, we would like to thank our families. Without their support we simply would not have completed this project.

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LIST OF ACRONYMS AND ABBREVIATIONS

AB3	Apache Block III
ASE	Aircraft Survivability Equipment
AT&L	Acquisition, Technology and Logistics
C2	Command and Control
CAPE	Cost Assessment and Program Evaluation
CIF	Contributing Influence Factor
COA	Course of Action
CPG	Co-pilot Gunner
CRT	Cumulative Retrofit Time
DoD	Department of Defense
EA	Evolutionary Acquisition
FCR	Fire Control Radar
GAO	Government Accountability Office
HADS	Helmet and Display Siting
HF	High Frequency
HPSS	High Performance Shock Strut
ISR	Intelligence, Surveillance, and Reconnaissance
MCDM	Multiple Criteria Decision Making
MDAP	Major Defense Acquisition Program
M-PNVS	Modernized Pilot Night Vision System
MTADS	Modernized Target Acquisition/Designation System
MTTR	Mean Time to Repair
MUM	Manned/Unmanned Teaming
OAT	One at a Time
ONS	Operational Need Statement
OSD	Office of the Secretary of Defense
PAUC	Program Acquisition Unit Cost
PEO	Program Executive Office

PM	Program/Project Manager
PMO	Program Management Office
POM	Program Objective Memorandum
QIS	Quality Index Score
RDS-21	Rotary Drive Shaft of the 21st Century
RPA	Retroactive Program Analysis
SITREP	Situation Report
TRL	Technology Readiness Level
UAS	Unmanned Aerial Systems
UAV	Unmanned Aerial Vehicle
USD	Undersecretary of Defense
UTA	UAS Tactical Common Data Link Assembly
VHF	Very High Frequency
VOC	Voice of the Customer

I. INTRODUCTION

A. BACKGROUND

Military program/project managers (PMs) are under ever-increasing levels of scrutiny to ensure that major acquisition programs meet cost, schedule, and performance goals. As budgets within the Department of Defense (DoD) decrease, PMs must take much greater care to optimize limited budgets and manpower resources in order to provide the greatest value to the taxpayer and the end user.

One of the most important decisions PMs make is how to optimally allocate resources among the various upgrade options for a given program. Trade-off decisions made by PMs when considering which upgrades to purchase are vital to ensuring value maximization during system upgrade projects. Generally, trade-off decisions involve identifying which upgrades are the most critical as well as the optimal amount of upgrades to purchase from a range of upgrade options, determining how best to allocate these across the force, and staying within the constraints of the budget.

In his *Better Buying Power 2.0* memorandum, Frank Kendall (current under-secretary of defense for Acquisition, Technology, and Logistics) stated that delivering better value to the taxpayer and warfighter by improving the way the DoD does business is his top priority (Kendall, 2012). Most applicable to this thesis, he mentioned that it is possible that programs will be halted if they do not factor cost trade-offs into their efforts to reduce the overall cost of the program. He also stated that unless these trade-offs are considered, “the Department will continue to spend billions on development and initial production of programs that are ultimately canceled or curtailed” (Kendall, 2012, para. 3). Optimizing trade-off decisions results in deriving the best overall value with the resources available. This report focuses on identifying a method to help PMs recognize potential cost trade-offs.

The primary approach to identifying such a method was the application of utility modeling, which is a tool that can assist decision-makers in quickly identifying optimal trade-off solutions for a given data set. Identifying and quantifying constraints is a critical aspect of utility modeling, and the process of identifying these constraints will assist PMs in making good trade-off decisions.

In order to find an optimal trade-off solution, individual upgrade quality must be defined for any given project. When using a utility model to assist in decision-making, quality must be quantified. This is often a difficult and time-consuming process because there are many factors that must be weighed when determining a quantitative value for quality. Factors such as cost, schedule impact, improved capability, fielding impact, maintainability, durability, ergonomics, and so forth all make up quality and these are unique to each program. Balancing the trade-offs between cost, schedule, and performance embodies the art and science of program management. This research project developed a utility model based on linear programming that can be tailored and applied to any DoD acquisition program to determine an optimal upgrade allocation (Balakrishnan, Render, & Stair, 2011).

In conducting our research, the authors used the Apache Block III (AB3) Modernization Program as a means to test the accuracy of the utility model. The AB3 Modernization Program is managed under Program Executive Office (PEO) Aviation at Redstone Arsenal, Alabama. The AB3 is an Apache attack helicopter modified to effectively and efficiently integrate the Longbow Apache well into the 21st century. The AB3 Modernization Program is a multi-billion dollar upgrade program that involves a wide range of upgrade options. The plentitude of upgrade choices presents an ideal testing ground for the utility model developed in this project.

The AB3 is designed to provide a significantly enhanced warfighting capability over the AH-64A and AH-64D models. Some of the improvements to the Apache include:

- Longbow fire control radar (FCR)
- Modernized Target Acquisition Designation System/Modernized Pilot Night Vision System (MTADS/M-PNVS)
- Longbow Hellfire missiles
- integrated command and control (C2)
- intelligence/surveillance/reconnaissance (ISR) improvements

- communications connectivity for attack/reconnaissance aviation within brigade combat teams, divisions, and corps
- improved engine performance and reliability (Department of Defense, 2012).

B. PURPOSE

The purpose of our research is to determine whether utility modeling based on integer linear programming can assist PMs in finding the optimal allocation of scarce budgetary and manpower resources for block upgrades to MDAPs. The goal of our research is to develop a utility model that can be applied to any DoD acquisition program to assist PMs in more effectively allocating resources.

C. RESEARCH QUESTION

Our primary question is: Can utility modeling be used to effectively find an optimal allocation of upgrade purchases when choosing from a range of potential upgrades? In this project, we consider a successful trial as an iteration wherein decisions made by PMs using the utility model are at least 90% consistent with decisions made using more methodical and time-consuming approaches. One such process is the program objective memorandum (POM) process, where a program's team intensely reviews all potential upgrades and develops a user-agreed optimal mix of upgrade solutions.

D. ASSUMPTIONS AND LIMITATIONS

This research project was written with the assumption that the reader has a basic understanding of the defense acquisition process and the role the PM has in making upgrade decisions as they pertain to the program that is being managed. In this research, we assume that the PM has the authority to decide how to optimally allocate budget and manpower resources to get the best overall value when making upgrade decisions.

Due to time and resource constraints in our research, we only applied this model to the AB3 Modernization Program. In order to refine the utility model further and to determine the model's usefulness, examining several programs is ideal. While conducting our research, we found that quality is a difficult element to quantitatively measure because it changes with each program. In the program we studied, getting a complete grasp and quantifying what quality is was a major factor in determining the effectiveness of the utility model.

E. METHODOLOGY

To conduct our research, we used several types of data and interviews to focus our efforts. We started with literature reviews of federal law, Office of the Secretary of Defense (OSD) guidance, academic journals, modeling textbooks, private and government websites, federal acquisition regulations, DoD instructions, government reports, and third-party books. Reviewing this literature provided us with a basic understanding of utility modeling and acquisition processes and helped us focus our research efforts. We also conducted extensive interviews with the PM of the AB3 Modernization Program.

When developing the model, we created a worksheet to derive the quality value of all potential upgrades being considered. We divided this worksheet into multiple categories and created a formula to generate a quality index. Next, we identified as many constraints that the PM has to contend with and can influence as possible. Once we developed all these factors, we applied them to the utility model to determine the optimal upgrade mix for a PM to allocate funds toward.

F. ORGANIZATION OF REPORT

The report is structured in a methodical way: (a) we lay the framework for the model (the requirements for and the theory behind the model), (b) we detail how the model was developed, (c) we apply the model, (d) we analyze the results, and (e) we present ideas for follow-on research and improvements to the model. In this chapter, we detailed the background and methodology for the report. In Chapter II, we summarize our literature review to provide a theoretical basis for modeling and to provide data on the AB3 Modernization Program. In Chapter III, we show how the model was constructed and present the upgrade options available to that program. It is in that chapter that we detail the PM's constraints in time and costs and show the quality ratings of the potential upgrades. In Chapter IV, we apply the model to the AB3 upgrade possibilities to determine the optimal amounts and types of upgrades. In Chapter V, we compare the results of the model to what was actually determined to be the optimal resource allocation by PM Apache. And in Chapter 6, we make our summary and conclusions regarding the model's effectiveness and recommend improvements and further research.

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II. LITERATURE REVIEW

A. EVOLUTIONARY ACQUISITION

When the DoD procures or develops a major weapon system or platform, the project is categorized as a Major Defense Acquisition Program (MDAP). The preferred strategy of program/project management for these procurement endeavors is called *evolutionary acquisition* (EA). EA is iterative and concedes that the nature of technology is continually developing. By allowing major weapon systems to be developed in steps, the DoD attempts to provide end users with functional, relevant equipment that is supportable and can be manufactured at a reliable rate. In EA, users employ the latest supportable version of a weapon or vehicle while the DoD is works to develop the next version. For MDAPs, these updates are called block upgrades. Each time an MDAP is upgraded, the goal is to add capability, relevance, utility, and reliability. The EA strategy works on small to medium programs such as personal weapon systems and ground/air combat platforms. EA cannot be applied to large and intricate systems such as aircraft carriers or submarines. For systems of that nature, upgrades represent an overhaul of the previous system design because they have extremely high effort-to-production unit ratios and because each new increment or evolution embodies a large number of new requirements. These platforms are manufactured at immense cost and either in small batches or one at a time. Finally, because these platforms remain in near constant service for three to four decades, it is cheaper to build entirely new ships rather than to overhaul the existing ones with all of the new technologies ("Evolutionary Acquisition Strategy," 2005).

Because EA is iterative, accurate estimation of overall program cost is very difficult. Since MDAPs can span multiple decades, unforeseen economic and geopolitical factors can cause increases in program length and cost that were originally not factored into calculations. For this reason, Congress has had some reservations about the DoD's adoption of EA as its preferred strategy for weapon systems acquisition (Lorell, Lowell, & Younassi, 2006).

The major benefit of EA is speed of delivery. By accepting that the perfect solution may be unattainable or decades in the making, EA aims to place the best current solution into the user's hands as quickly as possible. Rather than waiting empty-handed for perfection, users can continue to work while the DoD improves what is available to them. Additional benefits of EA include the potential to control cost growth and technical risk. Acquisition programs utilizing EA strategy are able to more accurately estimate short-term cost because the program is broken into smaller stages (block upgrades). Finally, there is a great deal of developmental flexibility associated with EA. Because the overall program is segmented into block upgrades, the developer has more time to gather real-world information about the current version in the field. While user feedback comes in, the developer is free to make refinements to the next version as it is being developed. This strategy has been applied successfully to systems such as the M-16 rifle, Abrams main battle tank, and the F/A-18 Hornet ("Evolutionary Acquisition Strategy," 2005).

Another example of EA is the DoD's acquisition of the AH-64 Apache attack helicopter. First fielded in 1983, the Apache has now undergone five versions and three block upgrades. The Apache Block III (AB3) program uses the AH-64D Longbow as a starting point for system upgrades and adds significant advancements in flight capability with the General Electric 701-D model engine and the Rotorcraft Drive System for the 21st Century (RDS-21). Combined with the High Performance Shock Strut (HPSS) system and new lighter, faster, stronger composite rotor blades, the RDS-21 allows the latest Apache more combat capability while regaining the maneuverability and hard landing capabilities of the first generation Apache. Additionally, the AB3 will allow the co-pilot gunner (CPG) to assume flight control and view feed from nearby UAVs. This capability has been named manned-unmanned teaming or "MUM" for short, and will assist the Apache crew in developing the tactical situation prior to arriving at an area to support ground operations (Osborn, 2012, para. 10).

B. WEAPON SYSTEMS ACQUISITION REFORM ACT OF 2009

After passing through the House of Representatives and the Senate unanimously, the Weapon Systems Acquisition Reform Act of 2009 was signed into law by President Barack Obama. This law makes multiple, sweeping reforms to the DoD acquisition system. Chief among these changes, the law installs a director of cost assessment and program evaluation (CAPE) within the DoD. The CAPE director reports directly to the secretary and undersecretary of defense and is charged with issuing policy on cost estimation and the confidence levels related to those cost estimates. The act absorbs the Office of Program Analysis and Evaluation into the CAPE, enabling the director to better develop new policies to bring policies on cost estimating back into line with congressional and executive guidance (Weapon Systems Acquisition Reform Act of 2009).

In addition to establishing the CAPE, the Weapon Systems Acquisition Reform Act of 2009 also amends the Nunn-McCurdy Act to allow the secretary of defense to rescind a previously granted milestone approval in the event that an acquisition program in question experiences severe cost overruns (Weapon Systems Acquisition Reform Act of 2009).

C. COST TRADE-OFFS IN ACQUISITION PROGRAMS

In November 2012, the USD(AT&L) Frank Kendall released a memorandum that stated his intention to further refine the DoD's acquisition system. The memorandum, titled *Better Buying Power 2.0*, lists seven major objectives designed to improve the DoD acquisition workforce's decision-making skills, enhance and sustain their professional development, and maximize value in every acquisition program the DoD pursues.

The first objective in Kendall's (2012) memorandum is titled "Achieve Affordable Programs." In this portion of the memorandum, Kendall (2012) illustrates the need to prioritize system requirements and to make cost trade-offs in order to keep all procurements within budget. By prioritizing system capabilities and performing cost trade-offs for individual upgrades within block upgrade programs, PMs may be able to meet the USD(AT&L)'s intent.

D. GAO REPORT OUTLINING THE IMPACT OF SEQUESTRATION ON MDAPS

The Government Accountability Office (GAO) Report 12-400SP, dated March 29, 2012, examined a selection of the 96 weapon systems currently in the DoD acquisition portfolio. The report revealed that in FY 2012, program costs grew by 5%, or $74.4 billion. Of this cost overrun, 42% were attributed to production inefficiency, 40% was blamed on quantity changes, and the final 18% was credited to cost growth in research and development (GAO, 2012).

The report also highlighted 13 future programs and contrasted them with some of the MDAPs that are responsible for high cost growth. In favorable contrast, the GAO report illustrated that these programs are working within the parameters set forth in the Weapons Systems Acquisition Reform Act of 2009 by emplacing affordability targets within their budget planning. This is also in keeping with the guidance set forth by the USD (AT&L)'s *Better Buying Power 2.0* memorandum. Additionally, the report commended these projects for their emplacement of "should cost analysis" in their decision-making procedure (GAO, 2012).

It is the position of this research project that utility modeling can help PMs to apply the parameters set forth by *Better Buying Power 2.0*. If PMs within the DoD acquisition system were able to quantitatively assess which individual upgrades provided the most value to their systems, then the acquisition workforce would be further enabled to maximize the value derived from each block upgrade to MDAPs. Unfortunately, it is very complicated and time consuming to assemble all of the pertinent schedule, cost, and quality information in order to make a simultaneous comparison of all prospective system upgrades that are presented to a PM.

E. INTEGER PROGRAMMING AND UTILITY MODELING

In their textbook *Managerial Decision Modeling with Spreadsheets*, Balakrishnan et al. (2011) defined integer programming as a mathematical method that is used to solve complex problems involving multiple inputs, constraints, and desired results. When writing an integer program, the first objective is to develop an objective. The objective is used to develop the rest of the model. Usually, the objective is either to maximize or minimize a variable (cost, profit, time, etc.). Once the objective has been developed, the next step is to program the decision variables. These variables represent all of the questions that the integer program intends to answer. These questions are most often found in binary (yes or no) or quantitative variables (how many). After the decision variables have been created, the programmer can derive the objective function. Essentially, the objective function is a mathematical illustration of how all decision variables will holistically affect the objective of the integer program. Finally, the program requires the installation of constraints. These act as arithmetic boundaries that help to shape an optimal solution to the overall problem that the integer program seeks to solve. In a production environment, constraints usually consist of things like time, materiel, budget, and so forth (Balakrishnan et al., 2011).

When programmed accurately and used properly, integer programs can assist in solving complex problems in a short amount of time. Because integer programs can analyze and compare many different variables and entry arguments, as well as simultaneously consider all the constraints that have been programmed, they can save decision-makers a great deal of time and money. However, integer programs are not a catch-all solution to quantitative problems. They are helpful in guiding a manager to an informed, quantitative analysis of a given question, but integer programs should not be used in a vacuum. Instead, these models should be used in concert with other proven decision-making and analytical tools to help guide a manager to the best possible production decision for his or her organization (Balakrishnan et al., 2011).

F. PROJECT MANAGEMENT IN THE DEFENSE ACQUISITION ENVIRONMENT

One of the main responsibilities of PMs is to manage their project to fruition and complete project deliverables within a set of constraints. These constraints shape the environment in which these deliverables are generated. Depending on the scope of the project, constraints may be numerous and complex, or simple and few. However, one set of constraints is constant regardless of a project’s size or scope. The triple constraints of quality (cost, schedule and quality) overshadow all other limitations that PMs work within and ultimately dictate the fate of projects. Project cost, schedule, and quality represent an unrelenting, co-dependent framework of considerations and decisions that the PM must make. By their very nature, when any two of these constraints are combined, they work to balance the third. As an example, cost and schedule constraints act to limit the amount of quality that can be achieved by a project. To further illustrate, if a stakeholder proposes additional quality for the deliverable, then either cost or schedule (sometimes both) must be increased.

In the 2012 edition of their book *Project Management for Engineering, Business and Technology*, John Nicholas and Herman Steyn listed more than 10 factors that contribute directly to the quality of a civilian project deliverable. Many of these factors readily translate into defense acquisition programs/projects. Areas such as system safety, reliability, adaptability, logistic supportability, negative trade-offs, and environmental impacts all represent significant concern to any successful military acquisition PM. However, each potential upgrade brings with it a unique combination of factors that must be carefully considered. PMs must consider the quality implications of each individual system upgrade separately from the weapon system as a whole. Once PMs fully understand what an individual upgrade brings to the table, they must consider how well its benefits and drawbacks mesh with the platform and program holistically (Nicholas & Steyn, 2012).

With respect to the AB3 Modernization Program, PMs have a great deal of individual upgrades to consider. While looking at the benefits and drawbacks to each upgrade, PMs must also consider funding and production schedule implications. Although a new upgrade may bring substantial capability to the AB3 platform, if the cost or schedule impacts are too extensive, then PMs cannot sponsor the upgrade for funding. Significant upgrades have already gained funding through the POM process, such as the RDS-21 system or the introduction of the General Electric Model 701-D engines (Osborn, 2010). However, PMs are still considering several additional upgrades to add to the AB3. As described previously, PMS must weigh the individual and holistic benefits presented by these upgrades against their impact to the PMs' overall production budget and schedule. Finally, PMs must develop a quantity recommendation for each new upgrade that will be proposed. Program Executive Office (PEO) Aviation requires the PM of the AB3 program to accompany each upgrade recommendation with a proposed quantity of aircraft to upgrade. This requirement underlines the need for the PM to perform in-depth quantitative analysis of the downstream effects that each upgrade will have on the program's overall budget. The following chapter discusses the methods we used in this research project to develop a utility-based, integer program model to assist PMs in these analyses.

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III. UTILITY MODEL DESIGN AND CONSTRUCTION

A. MODEL ARCHITECTURE

This research project yielded an integer linear program that is designed for use by PMs. The integer linear program is based in Microsoft Excel and utilizes the Solver data analysis tool to mathematically yield the most optimal results within preset constraints. The objective function or goal of the integer linear program is to maximize the added value of all system upgrades that will be procured as part of a larger upgrade to an MDAP. Ideally, the model solution will give PMs an optimal mix of upgrades to select and in what quantities. Essentially, this linear model helps PMs to answer the question, which upgrades should I select and how many should I buy? While developing the optimal solution, the model considers universal constraints that apply to any DoD weapon system procurement, such as schedule or budget. The model can also be easily customized to consider additional program-specific constraints such as small business inclusion, minimum or maximum system selection quantities, and so forth, should the user need them included. This model is not intended to provide PMs with a final answer to any acquisition question. It is intended to provide PMs with a quantitatively derived entry argument. The results of the model can also be used to “check” results of a previous analysis to determine whether a block upgrade program is on track to provide the best added value to the MDAP. The tool consists of three integrated systems. These systems work together to interface with PMs, to deliver PM inputs to the integer linear program, and to perform the integer linear program calculations.

B. EXCEL WORKSHEET

In designing and creating the utility model, our focus was to develop relevant inputs and an efficient method to organize them. In order to reduce the amount of models required, we designed an Excel worksheet to serve as an intermediary data entry platform. We programmed the worksheet to calculate the overall objective function and to organize other relevant inputs in a manner that can be easily used when inputting data into the utility model. The most difficult part of designing the worksheet and the utility model was to determine what the objective function would be. According to Balakrishnan et al., (2011) the objective function is “a mathematical statement of the goal of an organization, stated as the intent to maximize or minimize some important quantity” (p. 53). The goal of the utility model is to determine the optimal allocation of upgrade alternatives to achieve best overall value. As a result, the objective function is to maximize the overall value of the upgrade alternatives. According to the Federal Acquisition Regulation, “Best means the expected outcome of an acquisition that, in the Government’s estimation, provides the greatest overall benefit in response to the requirement.” (Federal Acquisition Regulation, 2005, sec. 2.101). To derive the overall benefit, cost, schedule, and quality factors must be considered to determine the ultimate benefit. The utility model compares each of these to attributes from each potential upgrade to find the optimal allocation of funding resources and achieve the best overall value for the taxpayer.

The Quality category is the most subjective and critical aspect of the utility model. According to the *Defense Acquisition Guidebook* (DoD, 2013), “Quality is the degree to which a set of inherent characteristics fulfills requirements.” Quality is such an essential aspect in determining the best overall value that we centered the objective function score of the utility model around it. Quality can be subjective, and in order for quality to be incorporated into the utility model, it must be quantified. The worksheet is the tool to quantify the subjective worth of the new or improved capability presented by the upgrade. Utilizing the worksheet, PMs can derive the objective function score or what is called the “quality index score” (QIS). The QIS is the score given to each upgrade that will be used to compare it against all others. Determining the QIS is the art and science of program management, and making this determination relies heavily on PM input. In the case of the AB3 Modernization Program, we examined 14 separate quality categories to determine the QIS. Considering more quality factors will result in a more complete QIS. The remainder of the worksheet is used to organize competitive influence factors, such as weighting and smoothing coefficients, and cost in a manner that is easy to input into the utility model. Cost is considered a constraint and is factored against the

QIS in the utility model. Without the generation of the QIS within the worksheet, the utility model cannot be used.

1. COMPETITIVE INFLUENCE FACTORS

The first category of the worksheet is the Competitive Influence Factors (CIF) section. As Figure 1 shows, the CIF section is where the upgrades are listed across the first row of the spreadsheet. Upgrades A through E in the example in Figure 2 represent the various upgrades to be considered. This section is critical to determining the overall quality of the potential upgrade.

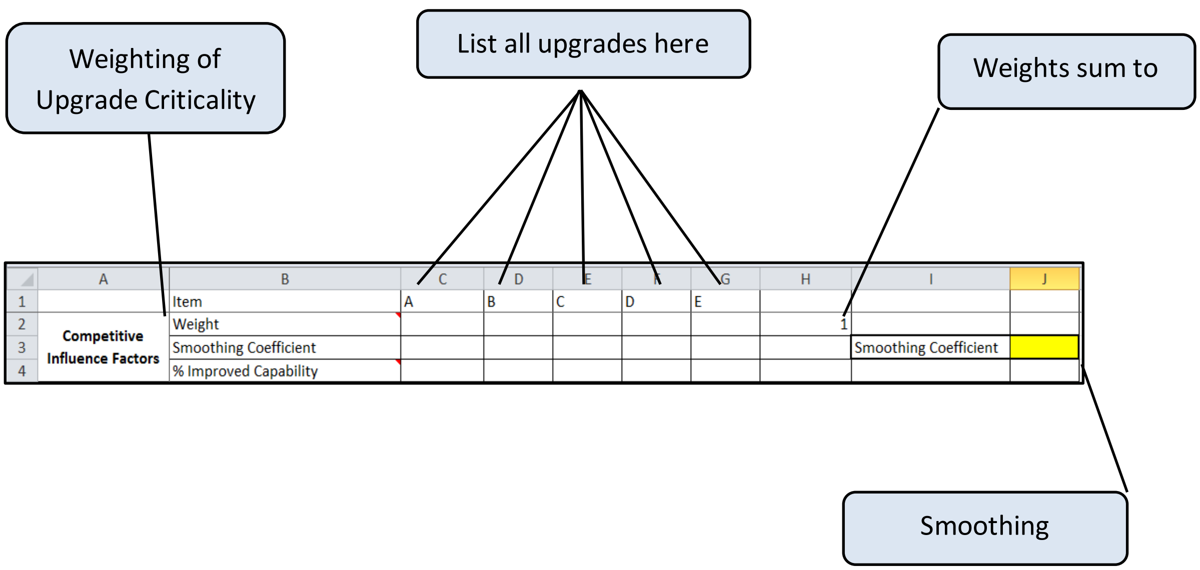


Figure 1. Competitive Influence Factors

Weighting: The first CIF factor in determining the best overall value is the upgrade's weight. Some upgrades may bring such a critical capability that they are given more importance to other potential upgrades relative to the decision-maker. Here, PMs are allowed to give that critical upgrade a higher weight than others to ensure it is accounted for in the end product. If all potential upgrades are equally valued, PMs can distribute the weights evenly, or simply leave the weight values blank. There are various methods to weight an upgrade. Weights can be listed in the following formats: in decimal form that either does or does not sum to 1 or in rank order (e.g., A = first place, B = second place…E = fifth place). For example, Upgrade A may get a weight of 5, while B and C get 2.5, and D and E get 1. It is paramount that weights are assigned in a uniform format in order to correctly weight the upgrade. Also, PMs must carefully consider the weight scores they award because weight plays a significant role in determining the final outcome of the utility model. PMs can also assign priorities to different upgrades according to their current assessment of the upgrade project. For instance, PMs could assign a score of 3, 2, or 1, respectively to each potential upgrade according to its importance with respect to the success of the MDAP block upgrade.

Smoothing Constant: The smoothing constant is a value greater than zero and less than one that is used to smooth out abrupt exponential fluctuations so that the model provides stable estimates. The higher the smoothing constant is, the smoother the total final score will be. If PMs are more interested in an aggressive upgrade portfolio, then they can utilize a lower smoothing constant. For a more balanced upgrade portfolio, PMs would choose a higher smoothing constant.

Percent Improved Capability: This is the overall improvement the proposed upgrade contributes to the system's current state. A 33% improvement is listed in whole numbers as 33 in order to ensure its value is accounted for in the overall scoring of the upgrades.

The next portion of the worksheet is concerned with the organization of the influence, quality, cost, schedule, and quantity categories. Figure 2 displays how we arranged these categories in conjunction with the listed potential upgrades. The top categories are influencing and quality categories, while cost, schedule, and quantity are constraint categories.

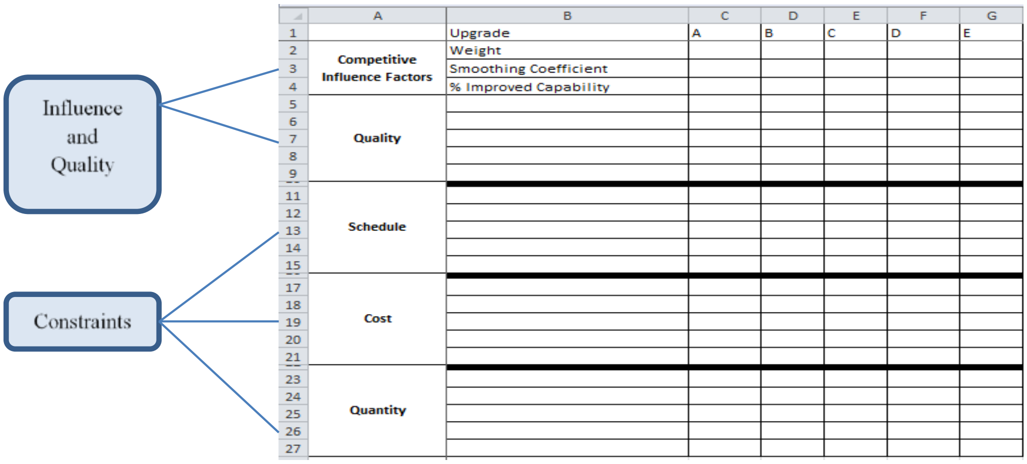


Figure 2. Worksheet Layout

2. QUALITY CATEGORIES

Each MDAP block upgrade is unique and requires a variety of skills and resources to successfully complete. Therefore, each block upgrade program must have unique factors to be considered in order to determine the quality of an upgrade. Within the Quality category, some basic quality factors should always be considered, along with the unique aspects of each program. These factors include performance, safety, reliability, ergonomics, maintainability, logistical support, environmental considerations, increased capability over the current state, technology readiness level (TRL), and small business employment. It is important to understand that the model we created in this research is not intended to compare upgrades that perform similar tasks; rather, our utility model is designed to compare disparate upgrades that provide unique capabilities. The purpose of the utility model is to identify trade-offs between technologies that are being considered in a block upgrade program. Within the quality category, PMs and their staff must develop as complete a list of quality factors as possible in order to achieve the most accurate and realistic QIS. The QIS (objective function) is based on the quality category. As stated earlier, cost and schedule factors are considered constraints; therefore, ensuring a complete understanding of quality is critical to obtaining the optimal trade-off. It must be noted that in some circumstances schedule can be used as a factor of quality rather than as a constraint. If PMs are making simultaneous assessments of potential upgrades, all of which promise an implementation timeline that fits within the PMs' schedules, then the PMs must instead assess which upgrades make the most economic use of their time. The use of schedule as a factor of quality allows PMs to frontload the upgrades that provide quality to the project in a timelier manner. We discuss schedule as a quality factor in further depth in the next section.

3. QUALITY SCORING METHODS

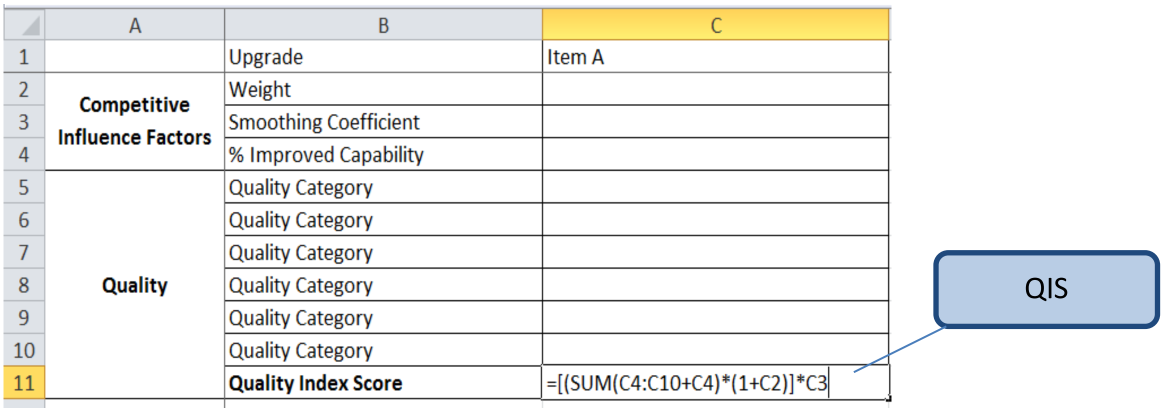
Each category listed in the quality portion of the worksheet is unique and may need to be rated in a unique manner. Table 1 lists several methods for rating a quality category in order to ensure an appropriate comparison of upgrades. A point system is used to compare each upgrade. When using the various rating types, a point total is determined based on PM inputs and assessments. These are summed at the completion of the evaluation process, and the QIS is determined for each potential upgrade.

Table 1. Rating Scales

1 to 10 Scale	In this data type, a scale from 1 to 10 is used to assess quality. Since maximizing overall value is the goal, 10 is the highest rating for a quality category and 1 is the lowest.
Yes/No (Binary)	In this example, 1 = yes and 0 = no. This data type is used in cases such as a small business consideration or when determining whether the upgrade meets a threshold. A *yes* answer receives 1 point and a *no* answer receives 0 points.
Percentage	This data type is used for increments, such as percentage of increased capability. For example, if a new radar system increases the effective range from 3 km to 4 km, then a 33% increase in capability is added. This is recorded as 33 points.
Subtracting Factors	This data type is used to subtract points in creating a negative impact to the current system in exchange for its new capability. For example, by adding extra armor to a vehicle, the fuel mileage and maneuverability of the vehicle are diminished. In this example, 1 = highest negative impact (least positive) and 10 = lowest negative impact (most positive).

4. QUALITY INDEX SCORE (QIS)

To determine the QIS, the worksheet calculates the sum of all quantities in the Quality category. The sum of the quality categories is multiplied by the weight assigned in the Competitive Influence Factors section. This is done for each potential upgrade. Figure 3 displays the Excel formula for QIS calculation.



	A	B	C
1		Upgrade	Item A
2	**Competitive Influence Factors**	Weight	
3		Smoothing Coefficient	
4		% Improved Capability	
5	**Quality**	Quality Category	
6		Quality Category	
7		Quality Category	
8		Quality Category	
9		Quality Category	
10		Quality Category	
11		**Quality Index Score**	=[(SUM(C4:C10+C4)*(1+C2)]*C3

Figure 3. QIS Calculation

5. SCHEDULE CONSTRAINTS

The schedule portion of the worksheet is used to annotate the impact the upgrade will have to the overall project either in terms of length of time to install the upgrade to the necessary units or in impacts to the PMs' personnel managing the project. If measuring the length of time to install the upgrade, worksheet users should input the standard time-measuring units that are used by PMs. For example, weeks, months, quarters, or years could be listed. If listing the impacts to the PMs' staff in terms of managing the project, worksheet users should use the standard time-measuring metric that is used within that PMO in other decision-making vehicles. For example, man years, weeks, months, or quarters of years could be used. Ensuring that the same time metric is uniformly applied to all upgrades is critical to producing a relevant comparison. Worksheet users may have to convert units of time to ensure they are being measured equally. For example, if one project takes two years to fully implement and another takes six months, then worksheet users may have to use 24 months or 0.25 years to ensure time measurement is consistent.

In many cases, PMs are not responsible for the actual production of the upgrade item that is being added to the MDAP (typically this is the contractor's responsibility). In such cases, the time it takes to produce the item then becomes a quality factor rather than a constraint. If evaluating several competing upgrades, shorter development time is better; therefore, this becomes a quality factor that should be accounted for. To account for schedule impacts (also known as cumulative retrofit time) within the QIS, a change to the overall QIS formula is required. To simplify accounting for such items, worksheet users should simply place into the model the amount of time (uniformly measured for all upgrades) it takes to retrofit the end item. For example, 24 is entered for 24 months within the quality factors. Since a longer retrofit time is less desirable, this must count against the overall QIS for the upgrade in question. The new formula accounting for the retrofit time is listed in Equation 1.

$$QIS = \left[\left(\sum Quailty\ Factors + \%\ Improved\ Capability\right) * (1 + Upgrade\ Weight)\right] * Smoothing\ Coefficient$$

QIS Formula 1

6. COST CONSTRAINTS

Cost is measured in dollars and should be comprised of the projected program acquisition unit cost (PAUC). Figure 4 shows how this should be listed in the worksheet.

Cost	Total Budget
	Upgrade A PAUC
	Upgrade B PAUC
	Upgrade C PAUC
	Upgrade D PAUC
	Upgrade E PAUC

Figure 4. Program Acquisition Unit Cost Constraint

7. QUANTITY CONSTRAINTS

Within the Quantity category, PMs will list the minimum and maximum units that they are able to purchase for each program. The quantity constraint will ensure that the PMs' ceiling and floor quantities are factored and measured in terms of units purchased. Minimums and maximums are listed together to simplify the data input into the utility model.

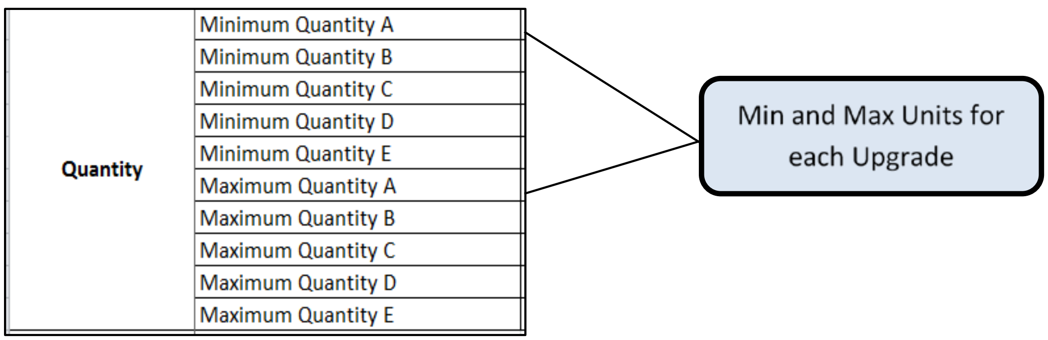


Figure 5. Unit Quantity Constraint

8. PROGRAM UNIQUE CONSTRAINTS

Other than cost, schedule, and quantity constraints, there may be times when additional unique constraints are required. There are three common alternative constraints that are most often utilized. Interdependency constraints, such as the ones listed in Table 2, can be programmed into the integer linear program portion of the utility model and can be used by PMs.

Table 2. Unique Constraint Types

Constraint Type	Example
Selecting *k* of *n* choices	For use when a certain amount of choices from a total amount must be selected. For example, out of five choices, at least three must be selected: $X_1 + X_2 + X_3 + X_4 + X_5 \geq 3$.
Mutually exclusive choices or avoiding incompatibilities	This type of constraint can be used in two scenarios. Scenario 1: No more than one upgrade can be installed from a group. An example of this would be selecting from upgrades that perform similar functions, such as choosing a type of tire from several tire options. Once a tire is selected, there is no longer a tire requirement. $X_1 + X_2 \leq 1$. Scenario 2: Selecting a specific upgrade ensures that some other upgrade cannot be selected. In this case, the upgrades are mutually exclusive. For example, if a wheeled chassis is selected, a tracked chassis cannot be used. $X_1 + X_2 = 1$.
If-then (linked) choices	If-then choices means that if Upgrade X_1 is selected, then Upgrade X_2 must also be selected. For example, additional radios are installed, then a larger alternator must also be installed. $X_1 \leq X_2$ shows a one-way linkage in that if A is installed, then D must also be installed, but not vice versa.

C. INTRA-MODEL DATA FLOW

As PMs answer the questions posed within the Excel worksheet, the data entered are referenced to the integer linear program. As an example, when PMs use the data field in the worksheet to assign a name to an upgrade program under consideration (e.g., High Performance Shock Strut), the same information replaces a generic placeholder (e.g., Upgrade A) with the name of the upgrade. The worksheet now “understands” that the first upgrade under consideration is called High Performance Shock Strut. All information provided by PMs regarding the High Performance Shock Strut is input and relayed from the worksheet to the correct place within the integer linear program.

As data is inputted into the worksheet, they are simultaneously “copied” and relayed to the integer linear program for computation. The title of the first decision variable began its life as Upgrade A and has now been transformed into High Performance Shock Strut on both the worksheet and the integer linear program.

Additionally, the automated data relay sends QIS values and constraint information from the worksheet into the integer linear program for computation.

To accommodate numerous or unique constraints, this research project constructed room for growth within the utility model to accommodate changes in constraints and variables as an MDAP program changes. Specifically, the worksheet has space for up to 20 potential upgrades. PMs can also provide program-unique constraints, such as minimum or maximum procurement quantities or upgrade dependencies. There are empty relational cells within the worksheet and the integer linear program that are ready to accommodate this data. If this additional or unique information is entered in the worksheet, it will be relayed to the integer linear program and will factor into computations. If no data is entered, the relational cells will remain empty and will have no impact on computation.

D. INTEGER LINEAR PROGRAM

The Excel-based integer linear program is simply the calculation engine for the quantitative assessment of the utility model. This research project developed it as a shell that can be customized to fit the decision variables and constraints of many different types of MDAP block upgrade programs. The integer linear program consists of an objective function, decision variables, and constraints. The objective function reflects the QIS scores that are developed by the PM within the worksheet tab and is the "answer" that the integer linear program must seek to maximize. It provides a quantitative solution that tells PMs how many of each upgrade to purchase in order to provide the best overall value to stakeholders.

Before the objective function can provide an answer, the integer linear program must receive decision variables from the Excel worksheet. These decision variables will be provided to the integer linear program, complete with QIS values that tell the model how much value they actually provide. Along with the QIS, each decision variable is assigned cost and schedule constraints. Additionally, PMs can add any project-unique constraints such as quantity minimum and maximums and dependencies. Through cell referencing, the worksheet will "tell" the integer linear program how long each upgrade will take to complete and how much it will cost.

Finally, the model will take into consideration any constraints that provide boundaries for a feasible solution. Along with cost and schedule restrictions, any additional constraints or dependencies that have been provided by the PM will make their way into the model and will be factored into the decision of the objective function. Once all information has been entered and PMs request computation, Excel will utilize the Solver extension to find the optimal solution. The solution is accompanied by the QIS information that has been entered by PMs. These data arm PMs with finite quantities of upgrades to purchase as well as quantitate value-added information. This data can either assist in the decision-making process or serve as a check against the PMs' current selection and decision-making process. Figures 6 and 7 display the Excel Solver declarations and objective function solutions, respectively.

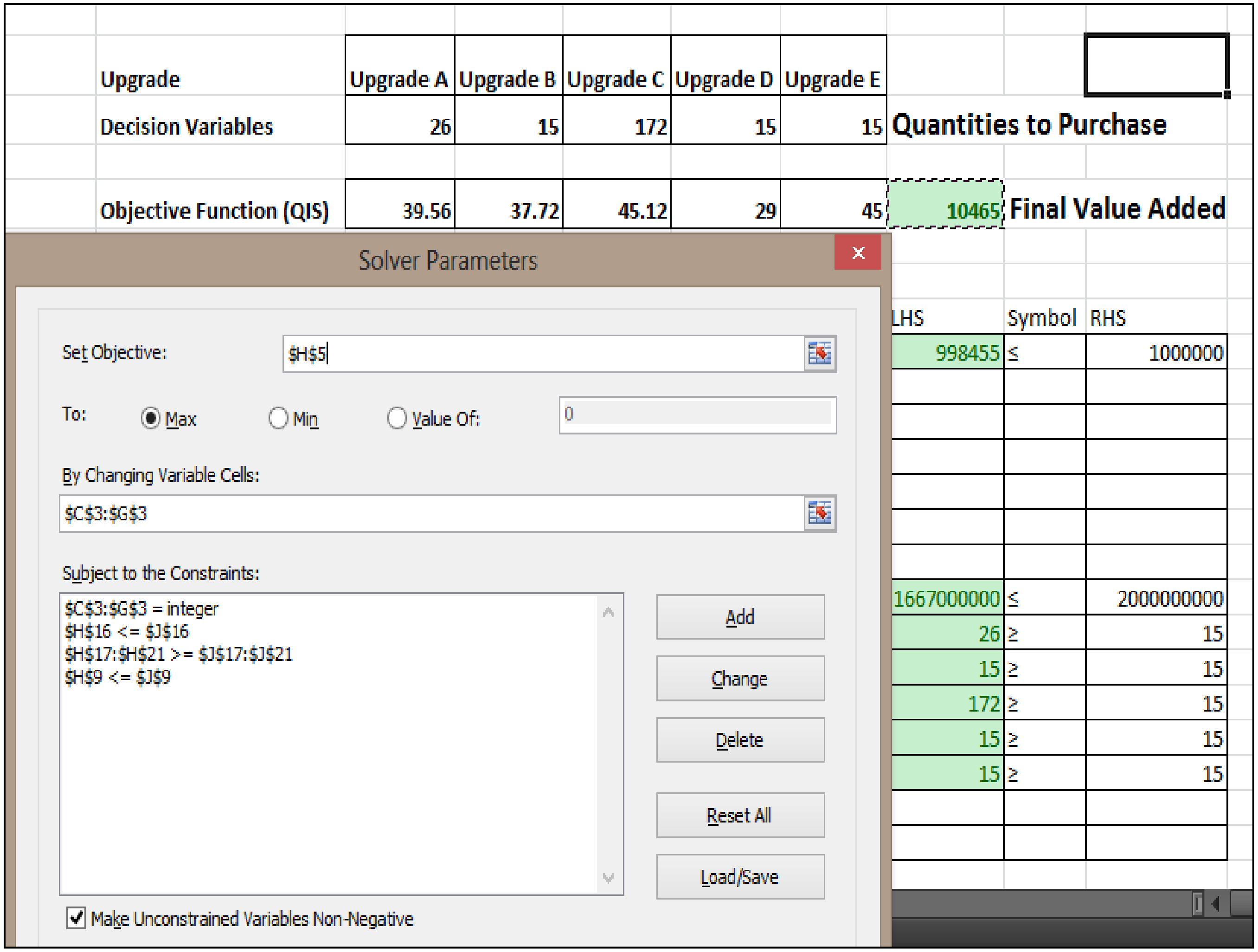


Figure 6. Excel Solver Declarations

Upgrade	Upgrade A	Upgrade B	Upgrade C	Upgrade D	Upgrade E		
Decision Variables	26	15	172	15	15	Quantities to Purchase	
Objective Function (QIS)	39.56	37.72	45.12	29	45	10465	Final Value Added

Figure 7. Objective Function Solution

IV. APPLYING THE UTILITY MODEL

A. EVALUATED TECHNOLOGIES

The PM for the AB3 Modernization Program provided this research project with 16 technologies to be evaluated using the utility model. These technologies allowed us to test and experiment with the utility model. Each of these technologies is unique in function and is mutually exclusive. Those technologies highlighted in Figure 8 represent a software-related upgrade. None of these technologies were included in the POM at the time we completed our assessment because they were being evaluated by the AB3 Modernization PM and his staff for integration in the AB3 Modernization Program.

Decaying Rotor Indication	Opposite Seat Fixed Gun Message
CMWS Indication	Secure Communications
FM Muting	Discrete, Selectable ASE Volumes
Certified PERF Page	Hydraulic Pressure Digital Readouts
AH-64E MTADS Jitter	Enhanced Transmission/Dual Accessory
Dual HADS Failure	UTA Weight/Capability (C, L, S, & UHF)
Remote HF Safety Fan (Display)	Seat Design
TADS Failure Weapon Inhibit	VHF Secure Communications

Figure 8. Evaluated Technologies. Highlighted Upgrades Are Software-related.

B. WORKSHEET CUSTOMIZATIONS

To be a useful tool, we had to make our model customizable to each program using it. In the case of the AB3 Modernization Program, the majority of the PM's customizations to constraints and quality factors were done on the worksheet. As stated in Chapter III, the more quality factors that can be included into the model, the more accurate the model's results. As the model was applied to the AB3 Modernization

Program, the PM added two new quality factors and adjusted two others from the original list. This increased the amount of quality factors to 14 for each of the 16 technologies to be evaluated. Figure 9 lists the final quality factors to be evaluated for the AB3 Modernization Program. Those factors highlighted in blue represent changed quality factors, and those highlighted in yellow are new factors.

	TRL Level
	Contracting Ease
	Training Time Implication
	Negative Impact
	Safety
	Reliability
	Source Value
Quality	Ergonomics
	Adaptability
	Mean Time to Repair (MTTR)
	Maintainability
	Logistic Support
	Environmental Impact
	Cumulative Retrofit Time
	Quality Index Score

Figure 9. AB3 Quality Factors. Factors Highlighted in Blue Are New Factors. Those in Yellow are Factors that Have Been Changed.

In the utility model's test application, using the AB3 Modernization Program, the PM changed the Small Business quality factor to Contracting Ease. This was changed because most small businesses cannot produce the technology on the scale or complexity required for the AB3 Modernization Program. The term *contracting ease* refers to the swiftness that PMs can procure new items. For example, it is more beneficial to the government if an item can be procured from a vendor who is already familiar with the project because this procurement can be done quickly.

The source value category refers to the origin of a requirement or idea. Potential upgrades that have spawned from the voice of the customer are given the highest quality factor score because they are considered an operational pull. Other sources of requirements are working groups with contractors or government integrators and are considered to be a technological push. Upgrades that seek to fill an operational pull are given more value because they seek to meet an immediate need of the customer in the field.

The mean time to repair (MTTR) category is the average time required to perform maintenance over a specific operating period. This quality factor is heavily valued by PMs because this time is derived during the development stage of the upgrade; therefore, it has more relevance to PMs when comparing various upgrades (Jones, 2006).

The cumulative retrofit time (CRT) factor is the time it takes to integrate the new technology onto the platform. The addition of this quality factor to the worksheet resulted in the removal of the schedule constraint because the PM for the AB3 Modernization Program is not responsible for actually building the new technology; the contractor is. As a result, the amount of time to produce, install, and fully integrate the item must be accounted for as a quality factor. The time in this case is listed in months (48 = 48 months to produce and integrate). What must be kept in mind is that the higher the score, the more negative the impact assessed to the overall QIS. This is opposite to the rest of the scoring on the quality portion of the worksheet. Up to this point, a higher numerical score has always been better to maximize the objective function. When considering time as a quality factor, the unique QIS formula displayed in Equation 2 must be used to penalize QIS scores for upgrades with longer CRTs and reward those with shorter CRTs.

$$QIS = [\left(\sum Quailty\ Factors + \%\ Improved\ Capability\right) * (1 + Upgrade\ Weight) - (Upgrade\ Weight * Cumulative\ Retrofit\ Time)] * Smoothing\ Coefficient$$

Figure 10. Unique QIS Formula

C. UNIQUE PROJECT CONSTRAINTS

In the case of the AB3 Modernization Program, software-related upgrades were a unique constraint that had to be considered. In the AB3 program, software-related upgrade purchase decisions are binary. If the model calculated that a single platform should receive a software-related upgrade, then each of the 790 platforms had to be upgraded. This decision is binary to mitigate the risk that could occur if the platforms are not interoperable. In this case, a binary constraint was put in place to ensure that if a software program was chosen, then each platform would receive the upgrade. To accommodate these unique decisions, we programmed customizations into the Excel Solver constraints and also into the decision variables themselves. These customizations applied only to the software-related upgrades and allowed the utility model to either calculate a fleet-wide, 790-piece purchase decision or decline the purchase completely.

D. WEIGHTING METHODOLOGIES

PMs can use one of several weighting methods to subjectively apply their preference to potential upgrades. Weight scores are a way for PMs to add a measured, subjective influence into an otherwise dispassionate equation. There are many reasons why PMs may wish to give certain upgrades a minor boost in a comparison with other upgrades. The most valid reasons for such an addition can be traced to either operational needs or personal experience. Most upgrades originate in operational needs statements (ONSs) from forward deployed areas where end users are finding shortfalls with their equipment. ONSs are an example of an operational pull that originates from the voice of the customer (VOC), or users in the field. Weighting potential upgrades allows PMs to make a stronger case for upgrades that fill a specified operational need within the confines of the model. Further, many PMs are assigned oversight of platforms that they have experience with. When we tested our model by applying it to the AB3 Modernization Program, we found that the PM was an AH-64 Apache pilot. This is considered an Army best business practice. The Army Acquisition Corps often appoints personnel with direct platform experience to serve as PMs. Personnel who have operated and managed a system stand a much greater chance of making valid and informed decisions with respect to that platform.

For the experimental application of this research project, the weighting methodologies utilized were ranking, summation, and prioritization. Each of these weighting methods has inherent advantages and drawbacks. The ranking method works well for assessments of between five and 20 potential upgrades, but causes large arithmetic "gaps" between those potential upgrades that receive the highest and lowest scores. The summation method works very well for assessments of five or fewer upgrades. The prioritization method works well for any sized group of potential upgrades because the resulting QIS scores most directly reflect the PMs' subjective preference. However, during the application of our model, the AB3 Modernization PM did not utilize a weighting method.

E. DATA INPUT AND QIS GENERATION

With the appropriate customized quality factors in place, the AB3 Modernization PM utilized the worksheet to make an un-influenced or optimized assessment of the 16 potential upgrades mentioned in Section A of this chapter. The PM decided to take an objective pass to see what decisions the model would make without any subjectivity in place. In order for the CRT quality factor to be taken into account, a default weight must be entered. In the absence of a default weight value, the CRT quality factor is reduced to zero, negating its influence on the QIS score. For an un-biased evaluation of each upgrade, the default weight value must be uniform. This research project recommends a default weight value of 1. Figure 11 displays the QIS scores that were computed by the utility model.

	Competitive Influence Factors			Quality														
Upgrade	Weight	Smoothing Coefficient	% Improved Capability	TRL Level	Contracting Ease	Training Time Implication	Negative Impact	Safety	Reliability	Source Value	Ergonomics	Adaptability	Mean Time to Repair (MTTR)	Maintainability	Logistic Support	Environmental Impact	Cumulative Retrofit Time	**Quality Index Score**
VHF Secure Communications	1	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	24	70.8
Seat Design	1	0.3	50	4	5	9	10	9	9	4	8	5	5	9	8	9	48	72
UTA Weight/Capability (C,L,S & UHF)	1	0.3	75	4	6	7	9	8	8	3	8	7	5	5	5	9	48	81
Enhanced Transmission / Dual Accessory	1	0.3	20	4	7	9	10	10	9	2	8	1	5	5	5	9	24	55.2
Hydraulic Pressure Digital Readouts	1	0.3	10	7	8	9	9	9	10	4	9	5	10	10	10	10	4	70.8
Discrete, Selectable ASE Volumes	1	0.3	25	5	7	9	9	9	9	1	9	7	8	9	8	10	18	69.6
Secure Communications	1	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	18	72.6
Opposite Seat Fixed Gun Message	1	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	12	67.8
TADS failure Weapon Inhibit	1	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	18	66
Remote HF Safety Fan (Display)	1	0.3	50	7	8	8	9	9	9	3	10	2	10	10	10	10	8	90.6
Dual HADS Failure	1	0.3	25	6	8	10	10	10	9	4	10	1	8	9	7	10	12	72.6
AH-64E MTADS Jitter	1	0.3	25	6	6	10	10	10	9	3	10	4	7	7	7	10	24	67.2
Certified PERF Page	1	0.3	100	5	7	8	10	9	10	2	10	5	5	8	10	10	6	117.6
FM Muting	1	0.3	20	6	7	9	10	10	10	4	10	5	10	9	10	10	4	76.8
CMWS Indication	1	0.3	50	5	7	8	9	8	10	1	9	7	10	9	10	10	4	90.6
Decaying Rotor Indication	1	0.3	50	5	8	9	9	9	10	3	10	5	10	10	10	10	2	94.2

Figure 11. AB3 Modernization Program Completed Worksheet: Control Data

The QIS scores generated for the 16 potential upgrades ranged from 55.2 quality points to 117.6. The average QIS score was 77.2. Eleven potential upgrades scored below 80, and the remaining five scored between 80 and 117.6 points. Regression analysis showed that the two most influential quality factors in the absence of PM weighting were Percent Improved Capability and TRL Level.

F. UTILITY MODEL RESULTS

In the application of our utility model, the AB3 Modernization PM was not searching for a satisficing answer that could be provided through weighted utility modeling with the weighting methods listed previously. Instead, he wanted an optimized solution that represented the best overall value for the portfolio, absent of exterior influence. To enhance the depth of this research project, we treated these optimized results as a control data set. We conducted three experiments in order to ascertain the impacts of weighted utility modeling and the different weighting methodologies within this utility model. The weighting methodologies utilized in these experiments were ranking, summation, and prioritization. Each of these weighting methods has inherent advantages and drawbacks. The control assessment results from the AB3 Modernization PM are displayed in Figure 12.

Upgrade	Decision Variables	Units to Purchase	Objective Function (QIS)	Added Quality Per Platform	Cost Per Quality Point	Cost Per Upgrade	Average Cost Per Accepted Upgrade	Final Value Added to Fleet	Projected Budget Expenditure
Decaying Rotor Indication	1	790	74418	94.2	$ 1.01	$ 94.94	$ 732.55	889836	$ 11,995,000.00
CMWS Indication	1	790	71574	90.6	$ 1.40	$ 126.58			
FM Muting	1	790	60672	76.8	$ 0.82	$ 63.29			
Certified PERF Page	1	790	92904	117.6	$ 10.76	$ 1,265.82			
AH-64E MTADS Jitter	948	948	67.2	67.2	$ 39.24	$ 2,637.13			
Dual HADS Failure	948	948	72.6	72.6	$ 1.09	$ 79.11			
Remote HF Safety Fan (Display)	948	948	90.6	90.6	$ 0.87	$ 79.11			
TADS failure Weapon Inhibit	1	790	52140	66	$ 0.77	$ 50.63			
Opposite Seat Fixed Gun Message	1	790	53562	67.8	$ 0.93	$ 63.29			
Secure Communications	1	790	57354	72.6	$ 26.15	$ 1,898.73			
Discrete, Selectable ASE Volumes	948	948	69.6	69.6	$ 18.19	$ 1,265.82			
Hydraulic Pressure Digital Readouts	1	790	55932	70.8	$ 4.47	$ 316.46			
Enhanced Transmission / Dual Accessory	358	358	55.2	55.2	$ 181.16	$ 10,000.00			
UTA Weight/Capability (C,L,S & UHF)	0	0	81	81	$ 455.80	$ 36,919.83			
Seat Design	0	0	72	72	$ 366.27	$ 26,371.31			
VHF Secure Communications	948	948	70.8	70.8	$ 22.35	$ 1,582.28			

Figure 12. AB3 Modernization Program: Control Results

The objective (control) results produced by the AB3 Modernization PM's optimized assessment provided a somewhat top-heavy and software-biased portfolio of upgrades. Each software-related upgrade was chosen. Additionally, hardware upgrades that were chosen included the following:

- Modernized Target Acquisition/Designation System (MTADS) Jitter
- Dual Helmet and Display Siting (HADS) Failure
- Remote High Frequency (HF) Safety Fan
- Discrete Selectable Aircraft Survivability Equipment (ASE) Volumes
- Very High Frequency (VHF) Secure Communications

The Enhanced Transmission/Dual Accessory upgrade was also chosen. However, the model only chose to purchase 358 of these upgrades, instead of the possible 948. Finally, the model declined to purchase the UTA Weight/Capability and the Seat Design upgrades. With a budget of $12 million, the utility model calculated the optimum portfolio depicted in Figure 12, costing $11,995,000.

The control results show very clearly that in "optimization mode", with all weight scores set at the default value of 1, the utility model is choosing upgrades that allow the cheapest addition of quality to the AB3 fleet. The utility model chose all of the software-related upgrades (binary, fleet-wide purchases). Additionally, the utility model chose fleet-wide purchases (all 790 helicopters plus 20% spares = 948) of each hardware upgrade with a cost per quality point of $39.24 and below. The primary reason for the partial purchase decision (Dual Accessory Upgrade) was also the cost per quality point. This upgrade had a cost per quality point of $181.16, indicating a price sensitivity zone wherein the model begins to find the marginal cost per quality point to be inequitable. Neither the UTA Weight/Capability nor the Seat Design upgrades were chosen for purchase due to costs per quality point of $455.80 and $366.27, respectively. These "no buy" decisions provide further evidence that a price sensitivity zone exists, as mentioned previously. These results prove that the measurement of marginal cost is central to the model's purchase decisions.

Our first experiment utilized rank weighting in the utility model worksheet. The weighting scores range from 16 (highest rank) to 1 (lowest rank). The assigned scores were randomized using Excel. Figure 13 displays the input data for the first experiment.

	Competitive Influence Factors			Quality														
Upgrade	Rank	Smoothing Coefficient	% Improved Capability	TRL Level	Contracting Ease	Training Time Implication	Negative Impact	Safety	Reliability	Source Value	Ergonomics	Adaptability	Mean Time to Repair (MTTR)	Maintainability	Logistic Support	Environmental Impact	Cumulative Retrofit Time	**Quality Index Score**
VHF Secure Communications	9	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	24	325.2
Seat Design	15	0.3	50	4	5	9	10	9	9	4	8	5	5	9	8	9	48	475.2
UTA Weight/Capability (C,L,S & UHF)	5	0.3	75	4	6	7	9	8	8	3	8	7	5	5	5	9	48	214.2
Enhanced Transmission / Dual Accessory	6	0.3	20	4	7	9	10	10	9	2	8	1	5	5	5	9	24	175.2
Hydraulic Pressure Digital Readouts	12	0.3	10	7	8	9	9	9	10	4	9	5	10	10	10	10	4	453.6
Discrete, Selectable ASE Volumes	1	0.3	25	5	7	9	9	9	9	1	9	7	8	9	8	10	18	69.6
Secure Communications	13	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	18	475.8
Opposite Seat Fixed Gun Message	14	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	12	485.1
TADS failure Weapon Inhibit	7	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	18	247.8
Remote HF Safety Fan (Display)	4	0.3	50	7	8	8	9	9	9	3	10	2	10	10	10	10	8	222.9
Dual HADS Failure	8	0.3	25	6	8	10	10	10	9	4	10	1	8	9	7	10	12	314.1
AH-64E MTADS Jitter	11	0.3	25	6	6	10	10	10	9	3	10	4	7	7	7	10	24	367.2
Certified PERF Page	16	0.3	100	5	7	8	10	9	10	2	10	5	5	8	10	10	6	986.1
FM Muting	3	0.3	20	6	7	9	10	10	10	4	10	5	10	9	10	10	4	152.4
CMWS Indication	10	0.3	50	5	7	8	9	8	10	1	9	7	10	9	10	10	4	492.9
Decaying Rotor Indication	2	0.3	50	5	8	9	9	9	10	3	10	5	10	10	10	10	2	141

Figure 13. First Experiment: Data

The randomly assigned rank scores are displayed across the second row of Figure 13. With rank scores entered into the worksheet, the QIS scores for the 16 potential upgrades change dramatically, ranging from 69.6 to 986.1. The average QIS score was 349.9. Six of the potential upgrades scored above 400 points, and the remaining 10 scored between 69.6 and 367.2 points. Regression analysis showed that with ranking scores in place, the two most influential factors in determining the QIS were the Rank and Percent Improved Capability factors. The results of the first experiment are shown in Figure 14.

Upgrade	Decaying Rotor Indication	CMWS Indication	FM Muting	Certified PERF Page	AH-64E MTADS Jitter	Dual HADS Failure	Remote HF Safety Fan (Display)	TADS failure Weapon Inhibit	Opposite Seat Fixed Gun Message	Secure Communications	Discrete, Selectable ASE Volumes	Hydraulic Pressure Digital Readouts	Enhanced Transmission / Dual Accessory	UTA Weight/Capability (C,L,S & UHF)	Seat Design	VHF Secure Communications
Decision Variables	0	1	0	1	664	474	284	0	1	1	95	1	15	0	232	569
Units to Purchase	0	790	0	790	664	474	284	0	790	790	95	790	15	0	232	569
Objective Function (QI$)	111390	389391	120396	779019	367.2	314.1	222.9	195762	383229	375882	69.6	358344	175.2	214.2	475.2	325.2
Added Quality Per Platform	#DIV/0!	492.9	#DIV/0!	986.1	367.2	314.1	222.9	#DIV/0!	485.1	475.8	69.6	453.6	175.2	214.2	475.2	325.2
Cost Per Quality Point	$ 0.67	$ 0.26	$ 0.42	$ 1.28	$ 7.18	$ 0.25	$ 0.35	$ 0.20	$ 0.13	$ 3.99	$ 18.19	$ 0.70	$ 57.08	$ 172.36	$ 55.50	$ 4.87
Cost Per Upgrade	#DIV/0!	$ 126.58	#DIV/0!	$ 1,265.82	$ 2,637.13	$ 79.11	$ 79.11	#DIV/0!	$ 63.29	$ 1,898.73	$ 1,265.82	$ 316.46	$ 10,000.00	$ 36,919.83	$ 26,371.31	$ 1,582.28
Average Cost Per Accepted Upgrade	#DIV/0!															
Final Value Added to Fleet	3046398															
Projected Budget Expenditure	$ 11,999,736.29															

Figure 14. First Experiment: Results

These results reflect preferences that were introduced into the system with the randomized ranking scores. The utility model declined to purchase three of the eight software-related potential upgrades (Decaying Rotor Indication, FM Muting, and TADS Failure Weapon Inhibit). This choice is in contrast with the control results, in which the utility model chose to purchase all eight. Further, in the presence of ranking inputs, the model declined to purchase the Enhanced Transmission/Dual Accessory or Discrete, Selectable ASE Volumes upgrades in significant quantities. Surprisingly, the utility model chose to purchase only 232 of the possible 948 Seat Design upgrades, despite that upgrade being ranked second. On further analysis, we attribute this decision to the high cost of the Seat Design upgrade ($26,371 per platform).

The utility model also decided to purchase a significant amount (284) of the Remote HF Safety Fan upgrade, despite that it was ranked twelfth. As in the Seat Design decision, the utility model used the relative value to influence the purchase decision since the HF Safety Fan costs $79 per platform. Statistical analysis showed the correlation coefficient between quantities purchased and rank to be 0.77 (very strong). However, the results also showed that rank alone was not a strong enough factor to entirely influence the utility model's decisions. Cost and value remained relevant factors. The correlation coefficient between cost-per-quality point and quantity purchased was -0.43, showing a significant negative relationship.

The results of this experiment show that the ranking method can be used as an effective way to apply a weighted influence in a multiple criteria decision-making (MCDM) framework, namely this utility model. They also show that the ranking method creates an appropriate and measured influence in purchase decisions, as seen in the Seat Design and Remote HF Safety Fan upgrades. In summary, a high rank score can help a potential upgrade in the utility model's calculations, but cost remains an important factor.

Our second experiment utilized the summation weighting method. This method assigns weighted value to entities according to an ordinal, pre-determined priority (chronology, cost, size, etc.). For the purpose of this experiment, we chose a non-influential priority, and the 16 potential upgrades were assigned summation weight values according to alphabetic order. Upgrades with titles starting closer to the beginning of the alphabet were assigned lower scores, and those with names starting closer to the end of the alphabet received higher scores. Table 3 displays the summation score assignment for this experiment in detail. Figure 15 displays the data for the second experiment.

Table 3. Summation Score Assignment for the Second Experiment

Upgrade Name	AH-64E MTADS Jitter	Certified PERF Page	CMWS Indication	Decaying Rotor Indication	Discrete, Selectable ASE Volumes	Dual HADS Failure	Enhanced Transmission / Dual Accessory	FM Muting	Hydraulic Pressure Digital Readouts	Opposite Seat Fixed Gun Message	Remote HF Safety Fan (Display)	Seat Design	Secure Communications	TADS failure Weapon Inhibit	UTA Weight/Capability (C,L,S & UHF)	VHF Secure Communications
Summation Weight	1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8

	Competitive Influence Factors			Quality													
Upgrade	Summation	Smoothing Coefficient	% Improved Capability	TRL Level	Contracting Ease	Training Time Implication	Negative Impact	Safety	Reliability	Source Value	Ergonomics	Adaptability	Mean Time to Repair (MTTR)	Maintainability	Logistic Support	Environmental Impact	Cumulative Retrofit Time	**Quality Index Score**
VHF Secure Communications	8	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	24	293.4
Seat Design	6	0.3	50	4	5	9	10	9	9	4	8	5	5	9	8	9	48	216
UTA Weight/Capability (C,L,S & UHF)	8	0.3	75	4	6	7	9	8	8	3	8	7	5	5	5	9	48	314.1
Enhanced Transmission / Dual Accessory	4	0.3	20	4	7	9	10	10	9	2	8	1	5	5	5	9	24	127.2
Hydraulic Pressure Digital Readouts	5	0.3	10	7	8	9	9	9	10	4	9	5	10	10	10	10	4	210
Discrete, Selectable ASE Volumes	3	0.3	25	5	7	9	9	9	9	1	9	7	8	9	8	10	18	133.8
Secure Communications	7	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	18	274.2
Opposite Seat Fixed Gun Message	5	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	12	196.2
TADS failure Weapon Inhibit	7	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	18	247.8
Remote HF Safety Fan (Display)	6	0.3	50	7	8	8	9	9	9	3	10	2	10	10	10	10	8	311.1
Dual HADS Failure	3	0.3	25	6	8	10	10	10	9	4	10	1	8	9	7	10	12	141.6
AH-64E MTADS Jitter	1	0.3	25	6	6	10	10	10	9	3	10	4	7	7	7	10	24	67.2
Certified PERF Page	1	0.3	100	5	7	8	10	9	10	2	10	5	5	8	10	10	6	117.6
FM Muting	4	0.3	20	6	7	9	10	10	10	4	10	5	10	9	10	10	4	190.2
CMWS Indication	2	0.3	50	5	7	8	9	8	10	1	9	7	10	9	10	10	4	135.3
Decaying Rotor Indication	2	0.3	50	5	8	9	9	9	10	3	10	5	10	10	10	10	2	141

Figure 15. Second Experiment: Data

The alphabetically assigned summation scores are displayed across the second row of Figure 15. With summation scores entered into the worksheet, the QIS scores for the 16 potential upgrades ranged from 67.2 to 314.1. The average QIS score was 194.8. Seven of the potential upgrades scored above 200 points, and the remaining nine scored between 67.2 and 196.2 points. Regression analysis showed that with summation scores in place, the three most influential factors in determining the QIS were the Summation Score, TRL Level, and Percent Improved Capability factors. The results of our second experiment are shown in Figure 16.

Upgrade	Decision Variables	Units to Purchase	Objective Function (QIS)	Added Quality Per Platform	Cost Per Quality Point	Cost Per Upgrade	Average Cost Per Accepted Upgrade	Final Value Added to Fleet	Projected Budget Expenditure
Decaying Rotor Indication	1	790	111390	141	$ 0.67	$ 94.94	$ 732.55	2001492.9	$ 11,998,966.24
CMWS Indication	1	790	106887	135.3	$ 0.94	$ 126.58			
FM Muting	1	790	150258	190.2	$ 0.33	$ 63.29			
Certified PERF Page	0	790	92904	117.6	$ 10.76	$ 1,265.82			
AH-64E MTADS Jitter	46	46	67.2	67.2	$ 39.24	$ 2,637.13			
Dual HADS Failure	948	948	141.6	141.6	$ 0.56	$ 79.11			
Remote HF Safety Fan (Display)	948	948	311.1	311.1	$ 0.25	$ 79.11			
TADS failure Weapon Inhibit	1	790	195762	247.8	$ 0.20	$ 50.63			
Opposite Seat Fixed Gun Message	1	790	154998	196.2	$ 0.32	$ 63.29			
Secure Communications	1	790	216618	274.2	$ 6.92	$ 1,898.73			
Discrete, Selectable ASE Volumes	948	948	133.8	133.8	$ 9.46	$ 1,265.82			
Hydraulic Pressure Digital Readouts	1	790	165900	210	$ 1.51	$ 316.46			
Enhanced Transmission / Dual Accessory	95	95	127.2	127.2	$ 78.62	$ 10,000.00			
UTA Weight/Capability (C,L,S & UHF)	95	95	314.1	314.1	$ 117.54	$ 36,919.83			
Seat Design	95	95	216	216	$ 122.09	$ 26,371.31			
VHF Secure Communications	948	948	293.4	293.4	$ 5.39	$ 1,582.28			

Figure 16. Second Experiment: Results

The results of our second experiment reflect influences that were introduced into the system with an alphabetized summation score assignment. The utility model declined to purchase only one of the eight software-related potential upgrades (Certified PERF Page). In contrast to all other results up to this point, the utility model purchased some of each hardware upgrade. In the control results, the utility model chose all eight software upgrades and six of the eight hardware upgrades. Despite being ranked first, the utility model only chose to purchase 95 of the possible 948 UTA Weight/Capability upgrades. Investigation showed that this decision was due to the high cost ($36,919 per platform) of UTA Weight/Capability upgrades. The utility model also decided to purchase the entirety (948) of the Discrete, Selectable ASE Volume upgrade, despite that it was ranked seventh. Like the UTA Weight/Capability upgrade, the utility model factored value into the calculation because the Discrete, Selectable ASE Volume upgrade is $1,265 per upgrade. Statistical analysis showed the correlation coefficient between quantities purchased and summation rank to be 0.19 (weak). The outcome of this experiment revealed that in an assessment of this size, summation weighting does not account for a significant amount of the purchase decision. Cost per upgrade proved to be the most influential factor. The correlation coefficient between cost-per-quality point and quantity purchased was -0.76, showing a very strong negative relationship.

The results of our second experiment show that the summation ranking method is a viable option for weighted utility modeling in order to derive satisficing answers within this utility model. However, this method should only be used in an assessment of ten upgrades or more when PMs wish to make a minor impact on the calculations of the utility model. In an assessment of this size, the summation method creates a much smaller influence than the ranking method. With the summation technique in place, a high rank score is not enough to cause a fully devoted purchase decision within the utility model. In order to be chosen for large quantity purchases, an upgrade must present a good value.

Our third experiment tested the use of priority ranking in the utility model. Prioritization uses a set of integer values to assign scores based on relative importance. The two most common applications of this method utilize either a 1 through 5 or 1 through 3 ranking system. In this research project, we utilized the 1 through 3 value system (3 is high and 1 is low). Priority ranks were randomly assigned to the potential upgrades using Excel. Figure 17 shows the data from the third experiment.

	Competitive Influence Factors			Quality														
Upgrade	Priority	Smoothing Coefficient	% Improved Capability	TRL Level	Contracting Ease	Training Time Implication	Negative Impact	Safety	Reliability	Source Value	Ergonomics	Adaptability	Mean Time to Repair (MTTR)	Maintainability	Logistic Support	Environmental Impact	Cumulative Retrofit Time	**Quality Index Score**
VHF Secure Communications	3	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	24	134.4
Seat Design	2	0.3	50	4	5	9	10	9	9	4	8	5	5	9	8	9	48	100.8
UTA Weight/Capability (C,L,S & UHF)	2	0.3	75	4	6	7	9	8	8	3	8	7	5	5	5	9	48	114.3
Enhanced Transmission / Dual Accessory	2	0.3	20	4	7	9	10	10	9	2	8	1	5	5	5	9	24	79.2
Hydraulic Pressure Digital Readouts	2	0.3	10	7	8	9	9	9	10	4	9	5	10	10	10	10	4	105.6
Discrete, Selectable ASE Volumes	3	0.3	25	5	7	9	9	9	9	1	9	7	8	9	8	10	18	133.8
Secure Communications	3	0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	18	139.8
Opposite Seat Fixed Gun Message	3	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	12	132
TADS failure Weapon Inhibit	1	0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	18	66
Remote HF Safety Fan (Display)	3	0.3	50	7	8	8	9	9	9	3	10	2	10	10	10	10	8	178.8
Dual HADS Failure	2	0.3	25	6	8	10	10	10	9	4	10	1	8	9	7	10	12	107.1
AH-64E MTADS Jitter	3	0.3	25	6	6	10	10	10	9	3	10	4	7	7	7	10	24	127.2
Certified PERF Page	3	0.3	100	5	7	8	10	9	10	2	10	5	5	8	10	10	6	233.4
FM Muting	2	0.3	20	6	7	9	10	10	10	4	10	5	10	9	10	10	4	115
CMWS Indication	3	0.3	50	5	7	8	9	8	10	1	9	7	10	9	10	10	4	180
Decaying Rotor Indication	3	0.3	50	5	8	9	9	9	10	3	10	5	10	10	10	10	2	187.8

Figure 17. Third Experiment: Data

The randomly assigned priority scores are displayed across the second row of Figure 17. With priority scores entered into the worksheet, the QIS scores for the 16 potential upgrades ranged from 66 to 233.4. The average QIS score was 133.4. Four of the potential upgrades scored above 150 points, and the remaining 11 scored between 66 and 139.2 points. Regression analysis showed that with priority scores in place, there are four influential factors in determining QIS: Priority, Percent Improved Capability, Contracting Ease, and Reliability (listed in order of influence). The results of our third experiment are shown in Figure 18.

Upgrade	Decision Variables	Units to Purchase	Objective Function (QIS)	Added Quality Per Platform	Cost Per Quality Point	Cost Per Upgrade	Average Cost Per Accepted Upgrade	Final Value Added to Fleet	Projected Budget Expenditure
Decaying Rotor Indication	1	790	148362	187.8	$ 0.51	$ 94.94	$ 5,517.58	1507912.8	$ 11,992,531.65
CMWS Indication	1	790	142200	180	$ 0.70	$ 126.58			
FM Muting	1	790	90534	114.6	$ 0.55	$ 63.29			
Certified PERF Page	1	790	184386	233.4	$ 5.42	$ 1,265.82			
AH-64E MTADS Jitter	948	948	127.2	127.2	$ 20.73	$ 2,637.13			
Dual HADS Failure	664	664	107.1	107.1	$ 0.74	$ 79.11			
Remote HF Safety Fan (Display)	948	948	178.8	178.8	$ 0.44	$ 79.11			
TADS failure Weapon Inhibit	0	0	52140	#DIV/0!	$ 0.77	#DIV/0!			
Opposite Seat Fixed Gun Message	1	790	104280	132	$ 0.48	$ 63.29			
Secure Communications	1	790	110442	139.8	$ 13.58	$ 1,898.73			
Discrete, Selectable ASE Volumes	948	948	133.8	133.8	$ 9.46	$ 1,265.82			
Hydraulic Pressure Digital Readouts	1	790	83424	105.6	$ 3.00	$ 316.46			
Enhanced Transmission / Dual Accessory	364	364	79.2	79.2	$ 126.26	$ 10,000.00			
UTA Weight/Capability (C,L,S & UHF)	0	0	114.3	114.3	$ 323.01	$ 36,919.83			
Seat Design	0	0	100.8	100.8	$ 261.62	$ 26,371.31			
VHF Secure Communications	948	948	134.4	134.4	$ 11.77	$ 1,582.28			

Figure 18. Third Experiment: Results

The results of the third experiment reveal the impacts of randomized priority values within the utility model. Like the optimized (control) solution set, the utility model did not purchase the Seat Design or UTA Weight Capability upgrades in the presence of priority values. These decisions can be attributed to the high cost of the two upgrades. Contrary to the control results, in the third experiment, the model did not purchase the TADS Failure Weapon Inhibit software-related upgrade, despite its relatively low cost ($50 per upgrade). Analysis showed that this decision was made because the TADS Failure Weapon Inhibit upgrade received the lowest possible priority score (a 1 out of a possible 3). The low priority score contributed significantly to a low QIS score (a 66 in this instance). Statistical analysis showed the correlation coefficient between quantities purchased and priority rank to be 0.78 (very strong). The outcome of this experiment revealed that in an MCDM assessment, priority ranking makes a meaningful influence on the purchase decision. Cost per upgrade proved to be the most influential factor. The correlation coefficient between cost-per-quality point and quantity purchased was -0.76, showing a very strong negative relationship.

The results from the third experiment show that prioritization can be used in MCDM. This method produced results that resemble the control results very closely. For this reason, we conclude in this research project that use of prioritization in an assessment of this size should be used only when PMs wish to make a small, but meaningful impact on the results of the utility model's assessment. This method noticeably influences purchase decisions for upgrades that receive the highest (and lowest) priority. Upgrades that are left in the middle are not given enough influence and are chosen based on their value alone. Upgrades that are given the highest scores are always chosen, unless they are prohibitively expensive, and those with the lowest scores are not chosen unless they provide high quality at a low cost.

We designed these experiments to test how the different methods affect the results of the utility model produced in this research project. They also served to ensure that the utility model would indeed factor the influences of weighted utility modeling into its calculations. The outcomes of the experiments allowed us to better understand how each method pairs with different MCDM scenarios. These methods have varying impacts on the results of the utility model's calculations. As discussed in the results of each experiment, some methods' impacts are less subtle and should only be used by PMs when appropriate. Table 4 provides a cross-section of the experimental results and the correlative relationships between the different weighted utility modeling methods and quantity purchase decisions.

Table 4. Experiment Results: Correlations to Quantities Purchased

Correlation to Quantity Purchased				
	Utility Model Type			
Factor	**Optimization**	**Weighted Utility Modeling**		
		Ranking	**Summation**	**Prioritization**
QIS	-0.112212194	0.745339082	0.151922701	0.559090478
Price/Upgrade	-0.930849728	-0.367408395	-0.732071087	-0.733143384
Input	N/A	0.769445798	-0.01687123	0.772208714

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V. UTILITY MODEL APPLICATIONS FOR PROGRAM MANAGEMENT

A. ASSESSMENT OF THE MODEL'S OVERALL UTILITY

The AB3 Modernization PM populated the worksheet of the utility model with the quality data from 16 potential upgrades. In this research project, the authors used this data to employ the model and generate an optimum solution. After the AB3 Modernization PM was presented with the results displayed in Figure 12, he felt the model would be a useful tool for educating his staff about the implications of their decisions in the form of procurement trade-offs. With regard to overall utility, the PM gave the model a rating of 8 out of 10. The PM also felt such a utility model would be very useful for new PMs because it would help them to quickly become familiar with the price and quantity sensitivities in their respective programs. For example, an increase in the quantity purchased of a certain item implies a decrease for another. The utility model also proved useful in analyzing the impacts that price increases or decreases had on quantities of upgrades that could be purchased and the second and third order effects to the program's overall optimal value. Finally, the PM stated that the model could be useful for conducting what-if scenarios, such as examining the impacts of budget cuts/increases and reporting these impacts to higher levels of decision-making authority.

B. CREATION OF THE PROGRAM DASHBOARD

One the benefits of consolidating information such as pricing, budget constraints, and quality factors into one location is the creation of a "dashboard" style method of presenting the current status of the MDAP block upgrade program. A dashboard is the consolidated presentation of information that has been pulled from various sources throughout an organization in a form that is easy to interpret. With all relevant data consolidated, it is much easier for a decision-maker to connect all the dots and to make better decisions when the impacts of a decision can be seen throughout the program rather than in a singular context. Another useful function of a dashboard is the ability to get a current assessment or situational report (SITREP) of where a program or mission currently stands. This is very valuable to decision-makers because they can rapidly respond to unforeseen events rather than take additional time to understand the current situation and then make decisions.

The utility model can provide a dashboard for the PM of any program if properly customized. By pulling the relevant cost, quality, and other constraints into a single interface, PMs can always have visibility as to where their program currently stands. As any one category changes or updates (for example, a contractor provides a final price for a potential upgrade), the update is immediately made to the utility model and the overall program can be recalculated. By having this granular level of instant situational awareness, decision-making is simplified and improved for the overall benefit of the program.

C. SENSITIVITY ANALYSIS

In their book, *Sensitivity Analysis*, Saltelli, Chan, and Scott (2000) defined sensitivity analysis as "the study of how variation in the output of a model can be apportioned, qualitatively or quantitatively, to different sources of variation, and of how the given model depends upon the information fed into it" (p.3). Our research project found that factor screening and global sensitivity analysis were most practical for this utility model. In order to provide the most useful information to PMs, the factor screening methods were limited to one at a time (OAT) global sensitivity analysis. OAT analysis calls for the manipulation of one variable, factor, or constraint at a time in order to assess the impact to the model's outcome. This sort of sensitivity analysis is the most useful for the purposes of this research project because it enables PMs to determine the relationships between individual quality factors, constraints, and QIS scores and their relationships to the optimum solution. Information about these relationships can help PMs better understand which factors are more important in adding quality to a platform and which constraints are the most limiting.

By using our utility model, PMs can pose hypothetical questions and assess potential program impacts. In this research project, we tested the model's sensitivity analysis capability with the evaluation of potential upgrades from the AB3 Modernization

Program. During the application experiment of our model, the AB3 Modernization PM changed the AB3 Modernization Program flexible budget amount, upgrade quantities, and upgrade prices. As a result, the PM was able to assess many possible scenarios simply by changing a few inputs within the worksheet portion of the utility model. In one sensitivity analysis assessment, the PM reduced the AB3 Modernization Program's flexible budget by 25%. As a result, the PM was able to instantly see the reduction in upgrade quantities the program was able to buy. Additionally, the PM was able to assess new price points for upgrades that would allow the program to purchase them in the same quantities. The PM "asked" the model all of these questions and received quantitative answers within a matter of minutes. The implication is that PMs could use sensitivity analysis to simulate or "war-game" any conceivable scenario. The AB3 Modernization PM noted that this analysis capability is very valuable because it would allow him to simulate changes to the most important factors that affect his program overall.

Sensitivity analyses regarding budget and prices are arguably the most valuable to PMs. However, the flexible nature of the utility model, and the customization of time as a quality factor (specifically for the AB3 program), would allow PMs to conduct analyses on any combination of quality factors. Because the model "sees" all of these factors as variables in an equation, they can be changed ad hoc, and new results can be produced for comparison. Results of sensitivity analyses regarding any of the quality factors that have been programmed in for the AB3 Modernization Program could potentially arm the AB3 Modernization PM with quantitative data when negotiating with vendors, fellow PMs, or PEO Aviation for more money, lower prices, better quality, and so forth.

Another vital purpose of sensitivity analysis is to test the accuracy of a model. In fact, Saltelli et al. (2000) stated that a mathematical model is not truly complete without a built-in capability to assess its accuracy. The utility model we produced in this research project is no exception to that rule. In order to produce this capability, we added a portion to the model; an additional tab in the Excel workbook titled Sensitivity Analysis. This tab is a carbon copy of the Solver tab, except that the decision variables were not programmed as integers. This allowed Microsoft Excel's Solver add-in to produce an itemized sensitivity analysis report. PMs could use this report to break out information regarding shadow prices, allowable price increases, and decreases for each variable of the model. This feature would provide PMs with a snapshot of sensitivities. We used this same report in this research project to assess the accuracy of the utility model.

D. WEIGHTED UTILITY MODELING

In this research project we approached the MDAP block upgrade process as an instance of multiple criteria decision-making (MCDM). The primary goal of the utility model we produced in this research project is optimization within the MCDM framework. That is, this utility model first seeks to find the best possible solution by working with multiple decision variables and constraints. This objective assumes no appointed motivations on the part of the PM. However, there are many instances in MDAP block upgrade programs when the PM does have predetermined goals and priorities. These arise from operational need, budgetary constraints, or any other number of exterior influences. In examples where the PM has clear goals to achieve within the MDAP upgrade program, weighted utility modeling comes into play.

If the AB3 Modernization PM were given a directive to achieve—such as give the AB3 Modernization Program 25% greater weight capacity and make the seat more ergonomic–then he would have clear goals to work toward. In the presence of these weighted variables, all non-related upgrades would take a backseat to those that would allow the PM to accomplish the goal of adding weight capacity and making the seat more ergonomic. Fortunately, the PM can program goals like this into the utility model. The weight factor in the Excel worksheet of the utility model allows the PM to use lexicographic (ordering or ranking), or weighted utility modeling methods, in order to accommodate any predetermined goals into calculations. Use of these methods essentially changes the objective of the model from optimization to satisficing, or finding the answer that the decision-maker needs.

When this utility model was applied to the AB3 Modernization Program, there were no programmatic goals. The AB3 Modernization PM simply wanted to know what the best mix of upgrades to purchase would be. In other words, he was looking for an optimized solution. However, in future scenarios, PMs could certainly apply weighted utility modeling in order to find solution sets that satisfice their goal requirements. In order to simulate the effects of weighted utility modeling in producing the results that PMs need, we conducted a simulation that reflects the scenario described previously. The PM is given the directive to add weight capacity and a more ergonomic seat. Figures 19 through 22 present the optimized and satisficing inputs and results from this simulation.

	Competitive Influence Factors			Quality														
Upgrade	Weight	Smoothing Coefficient	% Improved Capability	TRL Level	Contracting Ease	Training Time Implication	Negative Impact	Safety	Reliability	Source Value	Ergonomics	Adaptability	Mean Time to Repair (MTTR)	Maintainability	Logistic Support	Environmental Impact	Cumulative Retrofit Time	**Quality Index Score**
VHF Secure Communications		0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	24	39
Seat Design	0	0.3	50	4	5	9	10	9	9	4	8	5	5	9	8	9	48	43.2
UTA Weight/Capability (C,L,S & UHF)	0	0.3	75	4	6	7	9	8	8	3	8	7	5	5	5	9	48	47.7
Enhanced Transmission / Dual Accessory		0.3	20	4	7	9	10	10	9	2	8	1	5	5	5	9	24	31.2
Hydraulic Pressure Digital Readouts		0.3	10	7	8	9	9	9	10	4	9	5	10	10	10	10	4	36
Discrete, Selectable ASE Volumes		0.3	25	5	7	9	9	9	9	1	9	7	8	9	8	10	18	37.5
Secure Communications		0.3	25	5	6	8	9	10	10	4	10	7	8	8	10	10	18	39
Opposite Seat Fixed Gun Message		0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	12	35.7
TADS failure Weapon Inhibit		0.3	10	7	8	9	9	8	10	4	9	5	10	10	10	10	18	35.7
Remote HF Safety Fan (Display)		0.3	50	7	8	8	9	9	9	3	10	2	10	10	10	10	8	46.5
Dual HADS Failure		0.3	25	6	8	10	10	10	9	4	10	1	8	9	7	10	12	38
AH-64E MTADS Jitter		0.3	25	6	6	10	10	10	9	3	10	4	7	7	7	10	24	37.2
Certified PERF Page		0.3	100	5	7	8	10	9	10	2	10	5	5	8	10	10	6	60
FM Muting		0.3	20	6	7	9	10	10	10	4	10	5	10	9	10	10	4	39
CMWS Indication		0.3	50	5	7	8	9	8	10	1	9	7	10	9	10	10	4	45.9
Decaying Rotor Indication		0.3	50	5	8	9	9	9	10	3	10	5	10	10	10	10	2	47.4

Figure 19. Optimization Data Input

Upgrade	Decaying Rotor Indication	CMWS Indication	FM Muting	Certified PERF Page	AH-64E MTADS Jitter	Dual HADS Failure	Remote HF Safety Fan (Display)	TADS failure Weapon Inhibit	Opposite Seat Fixed Gun Message	Secure Communications	Discrete, Selectable ASE Volumes	Hydraulic Pressure Digital Readouts	Enhanced Transmission / Dual Accessory	UTA Weight/Capability (C,L,S & UHF)	Seat Design	VHF Secure Communications
Decision Variables	1	1	1	1	948	948	948	1	1	1	948	1	948	463	948	948
Units to Purchase	790	790	790	790	948	948	948	790	790	790	948	790	948	463	948	948
Objective Function (QIS)	37446	36261	30810	47163	37.2	38.1	46.5	28203	28203	30810	37.5	28440	31.2	47.7	43.2	39
Added Quality Per Platform	47.4	45.9	39	59.7	37.2	38.1	46.5	35.7	35.7	39	37.5	36	31.2	47.7	43.2	39
Cost Per Quality Point	$ 2.00	$ 2.76	$ 1.62	$ 21.20	$ 70.89	$ 2.08	$ 1.70	$ 1.42	$ 1.77	$ 48.69	$ 33.76	$ 8.79	$ 320.51	$ 774.00	$ 610.45	$ 40.57
Cost Per Upgrade	$ 94.94	$ 126.58	$ 63.29	$ 1,265.82	$ 2,637.13	$ 79.11	$ 79.11	$ 50.63	$ 63.29	$ 1,898.73	$ 1,265.82	$ 316.46	$ 10,000.00	$ 36,919.83	$ 2[illegible],371.31	$ 1,582.28
Average Cost Per Accepted Upgrade	$ 732.55															
Final Value Added to Fleet	547940.7															
Projected Budget Expenditure	$ 59,988,881.86															

Control Decision Results

Figure 20. Optimization Results

	Upgrade	Decaying Rotor Indication	CMWS Indication	FM Muting	Certified PERF Page	AH-64E MTADS Jitter	Dual HADS Failure	Remote HF Safety Fan (Display)	TADS failure Weapon Inhibit	Opposite Seat Fixed Gun Message	Secure Communications	Discrete, Selectable ASE Volumes	Hydraulic Pressure Digital Readouts	Enhanced Transmission / Dual Accessory	UTA Weight/Capability (C,L,S & UHF)	Seat Design	VHF Secure Communications
Competitive Influence Factors	Weight														3	3	
	Smoothing Coefficient	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	% Improved Capability	50	50	20	100	25	25	50	10	10	25	25	10	20	75	50	25
Quality	TRL Level	5	5	6	5	6	6	7	7	7	5	5	7	4	4	4	5
	Contracting Ease	8	7	7	7	6	8	8	8	8	6	7	8	7	6	5	6
	Training Time Implication	9	8	9	8	10	10	8	9	9	8	9	9	9	7	9	8
	Negative Impact	9	9	10	10	10	10	9	9	9	9	9	9	10	9	10	9
	Safety	9	8	10	9	10	10	9	8	8	10	9	9	10	8	9	10
	Reliability	10	10	10	10	9	9	9	10	10	10	9	10	9	8	9	10
	Source Value	3	1	4	2	3	4	3	4	4	4	1	4	2	3	4	4
	Ergonomics	10	9	10	10	10	10	10	9	9	10	9	9	8	8	8	10
	Adaptability	5	7	5	5	4	1	2	5	5	7	7	5	1	7	5	7
	Mean Time to Repair (MTTR)	10	10	10	5	7	8	10	10	10	8	8	10	5	5	5	8
	Maintainability	10	9	9	8	7	9	10	10	10	8	9	10	5	5	9	8
	Logistic Support	10	10	10	10	7	7	10	10	10	10	8	10	5	5	8	10
	Environmental Impact	10	10	10	10	10	10	10	10	10	10	10	10	9	9	9	10
	Cumulative Retrofit Time	2	4	4	6	24	12	8	18	12	18	18	4	24	48	48	24
	Quality Index Score	47.4	45.9	39	60	37.2	38	46.5	35.7	35.7	39	37.5	36	31.2	147.6	129.6	39

Figure 21. Weighted Utility Modeling Data Input

Upgrade	Decision Variables	Units to Purchase	Objective Function (QIS)	Added Quality Per Platform	Cost Per Quality Point	Cost Per Upgrade
VHF Secure Communications	948	948	39	39	$ 40.57	$ 1,582.28
Seat Design	948	948	129.6	129.6	$ 203.48	$ 26,371.31
UTA Weight/Capability (C,L,S & UHF)	720	720	147.6	147.6	$ 250.13	$ 36,919.[illegible]3
Enhanced Transmission / Dual Accessory	0	0	31.2	31.2	$ 320.51	$ 10,000.00
Hydraulic Pressure Digital Readouts	1	790	28440	36	$ 8.79	$ 316.46
Discrete, Selectable ASE Volumes	948	948	37.5	37.5	$ 33.76	$ 1,265.82
Secure Communications	1	790	30810	39	$ 48.69	$ 1,898.73
Opposite Seat Fixed Gun Message	1	790	28203	35.7	$ 1.77	$ 63.29
TADS failure Weapon Inhibit	1	790	28203	35.7	$ 1.42	$ 50.63
Remote HF Safety Fan (Display)	948	948	46.5	46.5	$ 1.70	$ 79.11
Dual HADS Failure	948	948	38.1	38.1	$ 2.08	$ 79.11
AH-64E MTADS Jitter	948	948	37.2	37.2	$ 70.89	$ 2,637.13
Certified PERF Page	1	790	47163	59.7	$ 21.20	$ 1,265.82
FM Muting	1	790	30810	39	$ 1.62	$ 63.29
CMWS Indication	1	790	36261	45.9	$ 2.76	$ 126.58
Decaying Rotor Indication	1	790	37446	47.4	$ 2.00	$ 94.94

Average Cost Per Accepted Upgrade	$ 732.55
Final Value Added to Fleet	684457.2
Projected Budget Expenditure	$ 59,997,278.48

Independent Decision Results

Figure 22. Weighted Utility Modeling Results

The results displayed in Figures 19 through 22 clearly show that weighted utility modeling can be used to find satisficing solutions in the presence of predetermined goals. In the control results, before weighted utility modeling is applied, neither the UTA Weight nor the Seat Design upgrades are selected by the utility model. However, once weighting utility modeling is applied, the utility model finds a solution that satisfices the goals while still selecting other upgrades in quantities that add quality to the portfolio.

Additionally, there may be instances in an MDAP block upgrade program that require constraints of mutual exclusivity. These constraints stipulate terms such as "upgrade X can only be purchased if upgrade Y is/is not purchased." Another unique quantity constraint is the *k* of *n* constraint, which indicates that "of upgrades X, Y, and Z, only two can be purchased." This research project addresses these types of unique constraints in detail in Chapter III. In events where these constraints are present, weighted utility modeling could be applied to the variables one at time to counter the mathematical deviations encountered within Excel Solver in order to derive a solution. Solutions of this nature may not assist PMs in quantity-based decision-making. However, these solution sets could assist PMs in developing a better understanding of finite values within the upgrade program and their relationships to one another.

In other MDAP block upgrade programs, PMs may bear a heavy disposition toward certain upgrades due to exterior influences such as DoD objective programming or public/Congressional pressure. Weighted utility modeling has significant value when PMs need the model to "choose" a pre-determined upgrade in a set quantity and still reach an optimal solution that includes all potential upgrades.

E. EDUCATION OF PROGRAM STAFF

Ensuring that each member of a program staff has good situational awareness of the program will reduce misunderstandings and miscommunications both internally and externally. Lapses in situational awareness often lead to friction within a program that could result in unnecessary delays and costs and in less than optimal value for the taxpayer. By using the utility model in a dashboard format for all of the relevant staff in a program, the staff becomes educated about the effects their individual decisions have on the overall program. This helps each member to see the overall picture and to make more informed decisions within their scope of responsibility. The AB3 Modernization PM felt this type of education would help his staff meet the overall program goals. Additionally, this model would help newer staff members learn the breadth of the program by seeing how all the program's parts interact with each other.

F. DECISION-MAKING SUPPORT

In large programs where dozens of stakeholders are involved and budgets are in the hundreds of millions of dollars, it is often difficult to make a good and complete decision because it is hard to see decision alternatives and because not all necessary information is available. When combining uncertainty such as future budget amounts, requirements changes, quality factors, unforeseeable issues, and large dollar amounts, it is vital that each decision be thoroughly researched since poor decisions can be very disruptive and expensive. The use of our utility model could reduce some of the unknown implications a decision carries and could result in better overall decisions. Decision-makers must first define the problem (ID constraints and quality factors), list the alternatives (customize the worksheet), identify future outcomes for each alternative (sensitivity analysis), identify payoffs or costs for each decision (run the utility model), and finally make a decision. The utility model's results feed nicely into other decision-making models such as maxi-max/maxi-min, criterion of realism, equally likely, or decision trees. By combining the utility model and other decision-making models as a compound data analysis tool, PMs can make more accurate and robust decisions (Balakrishnan et al., 2011).

The model can provide quantitative support for recommendations a PM might make above his own echelon (such as at the PEO level). The utility model provides the ability to conduct various decision analysis techniques, which in the long run will result in successful outcomes for the entire organization if conducted properly.

G. PROGRAM MANAGEMENT OFFICE CONTINUITY

Continuity may be the lifeblood of a program management office. Over the course of an MDAP's life, it is certain that there will be multiple changes to all of the factors that directly affect its success. Because the DoD uses evolutionary acquisition (EA) as its preferred method for the acquisition of platforms such as the AH-64 Apache attack helicopter, the program/project management office (PMO) could last decades. Over those years, the nature of the program, its budgetary constraints, its systems and personnel are subject to significant turnover. No researcher could hope to develop a utility model that would encompass, process, and manage all of that change. However, in the right hands, a utility model can help PMs navigate change.

MDAPs are subject to change with the needs and requirements of the DoD. Therefore, a program that is alive and healthy one day may be cancelled the next due to budgetary constraints. This utility model is designed to help PMs optimize a solution set in an MCDM framework. If the AB3 Modernization Program were declared to be the final installment of the Apache block upgrades, then the PM would have to make decisions about how to close out the program in the most economic manner. This utility model could easily be customized with decision variables that would assist in this process.

PMs understand that nothing can be accomplished without budgetary resources, and the more a PMO has, the more it can accomplish for the MDAP. However, money is never guaranteed, and it often varies greatly from year to year. During times of conflict, MDAPs often enjoy a greater amount of funding in order to add capability for warfighter use. In times of peace, money is often programmed away from the DoD and thus the wells for the MDAPs dry up. PMOs are forced to do more with less. Although maintaining continuity in these times can be difficult, a utility model can help PMs maintain funding for priority efforts. It can even help PMs prepare and simulate future fiscal constraints if budget cuts are looming. Performing simulations can help PMs to prepare future courses of action (COAs) for their successors.

As mentioned previously, there are times when the role of an MDAP may be expanded. These expansions can result from another program’s cancellation, from a contemporary requirement, or from new developments in technology. An example of role expansion is the AB3 Modernization Program’s new role to simultaneously manage and utilize unmanned aerial systems (UAS) while on station. With each new role taken on by a platform comes a suite of new systems. In order to accommodate the new UAS-related role, the AB3 Modernization Program added the Manned/Un-manned Teaming (MUT) suite of systems. The addition of a new system to a platform can prove complicated. Adding five systems simultaneously could closely represent chaos. However, use of a utility model implies a simple adaptation of the model to accommodate the new systems. Simulations can immediately be run to determine what impact the presence of the new systems will have on budget and purchase quantities.

Personnel are also subject to change within a PMO. Military PMs often serve in their billet for three years or less, while their civilian counterparts remain in their positions for an average of 12 years (Riley & Fallesen, 2013). With this much turnover among military leaders, it is easy to imagine how data could get lost in the shuffle. However, if data corresponding to cost, quality, and schedule are stored and maintained using a utility model, then there is less chance that vital information will become outdated or slip through the cracks as leaders transition in and out of their roles within a PMO.

In conclusion, there is no single tool that can serve as a "catch all" to maintain 100% continuity within a PMO. A utility model cannot solve all continuity-related problems that arise from changes in a program's situation, budget, systems, or personnel. Instead, a utility model represents one piece of a potential solution set that can assist PMs in managing the ever-changing environment that defines an MDAP.

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VI. SUMMARY, CONCLUSION, RECOMMENDATIONS FOR FUTURE RESEARCH

A. SUMMARY

Throughout this project, we have attempted to answer our original research question: Can utility modeling be used to effectively find an optimal allocation of upgrade purchases when choosing from a range of potential upgrades?

Using the AB3 Modernization Program, we were able to answer the research question by using a real-world MDAP upgrade. The AB3 Modernization Program proved to be an excellent illustration to answer the research question because of the wide range of potential upgrades that the PM was considering for purchase. At the time this study was conducted, the AB3 Modernization PM was considering 16 technologies with different functions, prices, schedule impacts, and trade-offs. These upgrades involved hardware and software and improved the AB3 platform in different manners and degrees. The challenge for the PM was finding a way to optimally distribute his budgetary resources to achieve the optimal value for the taxpayer and the warfighter.

To effectively employ linear programming, the objective must be to maximize or minimize the objective variable. In the case of the AB3 Modernization Program, the goal was to maximize taxpayer value and provide the most capable platform for the end user. With the goal of maximizing total utility, the objective function is to maximize the overall quality of the various upgrades being considered within the constraints presented by each. To assess quality, we developed a method to determine the marginal improvement offered by each potential upgrade. Because each potential upgrade performed a different function, we had to ensure we were comparing each item equally. To do this, we developed an Excel worksheet that summed the various quality factors into a final score. This final score was called the quality index score, or QIS. The QIS is the value to be maximized, and it facilitated the use of linear programming in our research.

The goal of this research project was to determine whether utility modeling could be used in the DoD acquisition decision-making process. In order to answer this question, we designed and programmed a utility model that could be customized to fit any DoD MDAP block upgrade program. The assessment data we used allowed us to answer two questions that were central to our thesis: (1) Does the utility model return a feasible solution? and (2) What are the results of the PM's assessments?

To be considered functional, the utility model must provide purchase decisions for the potential upgrades being considered while maximizing quality. The model must provide these answers in two modes: optimizing and satisficing or weighted utility modeling. Finally, the model must provide sensitivity analysis for the PM. In optimization mode, there is no way for a PM to provide subjectivity. Regression and correlation analyses of the results from this mode showed that the utility model made purchase decisions based purely on cost and QIS. The results were optimal because there was no other possible solution that offered more quality for the AB3 fleet within the same budget. This is exactly the answer that the optimization mode was designed to find. In weighted utility modeling mode, the model must provide the PM with answers that satisficed certain external influences or tastes. As part of this research project, we conducted experiments to test the three weighted utility modeling methods that are most relevant to MCDM: ranking, prioritization, and summation. Analysis of the results revealed that all three methods are relevant, but they have different effects on the outcome of the utility model's decisions. Further analysis helped us to map these methods with appropriate scenarios. In both modes of the utility model, sensitivity analysis allows the PM to determine shadow pricing and price/quantity sensitivities. Additionally, sensitivity analysis allowed us to determine the accuracy of the model's calculations.

Analysis of the model's results allowed for better understanding of the logic that drove purchase decisions. In this research project, we interpreted the purchase decision results in terms of the quantity to purchase metric. We developed two metrics within the utility model to help understand and track our results: the QIS and the price-per-quality point. Correlation data for these metrics showed that price/value is always an overarching factor in decisions (as it should be). Regression analysis also showed that factors such as percent improved capability and TRL were more influential than others. This is appropriate to the acquisition decision-making environment because technology maturity and marginal benefits often drive an upgrade's success. Data analysis allowed for a deeper understanding of which quality factors drive overall upgrade attractiveness and also showed how relationships with cost drive optimized and satisficed decisions.

B. CONCLUSION

The results of this research project prove that linear programming and utility modeling can positively contribute to the DoD acquisition decision-making process in several ways. A PM, or a member of the program/project management team, can use utility modeling to arrive at optimized or weighted results regarding a side-by-side comparison of many potential upgrades. Further, the user can apply a sensitivity analysis to the results to determine important factors such as shadow prices and price-to-quantity sensitivities.

The results or purchase decisions of an adequately programmed utility model are granular, value based, and easy to interpret. Because of this, they have many uses in the acquisition decision-making environment. PMs can apply utility modeling at the outset of a program's phase and use the results as a beginning point for deeper upgrade assessments like the POM process. The results can also be used to quantitatively demonstrate a PM's position when negotiating with the PEO for more funds/time or with a vendor for better prices/greater quantity. Further, utility modeling can be used to educate staff members or to help with continuity during times of transition. Finally, because utility modeling is flexible and provides answers quickly, PMs can use it to simulate any situation that can be quantitatively modeled. In this capacity, utility modeling can be an invaluable planning and situational analysis tool.

Utility modeling fills a very important void in the acquisition decision-making environment: the ability to quantitatively and simultaneously compare many potential upgrades. Utility modeling can provide PMs with an unprecedented level of situational awareness and understanding within their program. Nested within the first tenet of USD(AT&L) Kendall's (2012) *Better Buying Power 2.0*, utility modeling provides PMs with the ability to make optimal cost trade-off decisions and to maximize the value and quality of their portfolios. PMs can also profit from mathematical data, plan for the future, and maintain education and stability within the PMO.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

While conducting research for this project, we identified several areas in which future research could expand or improve the functionality of utility modeling as it is applied to program management within the DoD:

- Forecasting involves techniques that attempt to reduce uncertainty. A quality forecast can help PMs make a good prediction about what will occur in the future (Hillier & Lieberman, 1995). This allows PMs to make better decisions regarding the future course of their programs. In making better predictions about future issues, PMs must understand which program data is paramount and then map it to the proper forecasting method.
- According to Hillier and Lieberman (1995), “Game Theory is mathematical theory that deals with the general features of competitive situations like these in a formal, abstract way. It places particular emphasis on decision making processes of the adversaries” (p.470). Within game theory, utility modeling can be applied to solve a game with mixed strategies. How would PMs utilize game theory to gain an advantage over a contractor in negotiating prices, quality features of upgrades, or other negotiated aspects of program management? Could forecasting, simulations, and sensitivity analyses lead to predictions that could be applied to utility modeling game theory?
- Retroactive Program Analysis (RPA) is the application of utility modeling to past MDAP block upgrade programs. It is applied in order to learn from previous successes or failures. This sort of analysis could benefit a PMO because the results could lead to a deeper understanding of why past programs were effective or fruitless. These lessons could help recreate successes and avoid the pitfalls of previous programs. PMOs should apply utility modeling to past MDAPs to gain further awareness of cost trade-offs and the positive application of utility modeling in MCDM. RPA is best utilized at the outset of a DoD acquisition effort or in an academic setting. Utility modeling could be applied to previous DoD acquisition programs in the same way that it was applied to the AB3 Modernization Program in this thesis.

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